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DEFORMATION PROCESSING OF NICKLE-BASE AND COBALT-BASE ALLOYS

By D. E. Strohecker, T. G. Byrer, A. F. Gerds, J. H. Gehrke, and F. W. Boulger

Prepared Under the Supervision of the
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ABSTRACT

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This report covers the state of the art of both primary and secondary fabrication methods for the nickel- and cobalt-base alloys. Methods currently employed for primary fabrication of these alloys include rolling, extrusion, forging, and drawing of tube, rod, and wire.

Secondary metal-forming operations are those processes that produce finished or semifinished parts from sheet, bar, or tubing using additional metal-forming operations. The following secondary forming processes are discussed: brake bending, deep drawing, spinning and shear, drop hammer, trapped rubber, stretch, tube, roll, dimpling, joggling, and sizing. Equipment and tooling used for the various operations are discussed and illustrated wherever possible.

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PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report on practices used to deform nickel-base and cobalt-base alloys into useful shapes is intended to provide information that may be of use to designers and fabricators. The recommendations are considered to be reliable guides for selecting conditions, tools, and equipment for specific operations. The causes for many of the common problems encountered are identified, and precautions for avoiding them are mentioned.

The report summarizes information collected from equipment manufacturers, technical publications, reports on Government contracts, and by interviews with engineers employed by major aircraft companies. A total of 78 references are included, most of which cover the period since 1959.

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TECHNICAL MEMORANDUM X-53439

DEFORMATION PROCESSING OF NICKEL-BASE AND COBALT-BASE ALLOYS

SUMMARY

Nickel- and cobalt-base alloys have been fabricated both by primary and secondary forming techniques that are very similar to those used to fabricate the stainless steels. The alloys generally are resistant to corrosion, and this property makes them attractive for applications in marine environments and in the chemical-processing industry. Although these alloys are 1.4 to 1.5 times heavier than steel, their generally higher elevated-temperature strength has made them available for applications in the aircraft and aerospace industry, where strength at temperatures higher than those obtainable with the steels, stainless steels, and other alloys are encountered.

The rolled products, sheet, plate, and rod, comprise the largest market for the nickel and cobalt alloys in aircraft and aerospace applications. Seamless nickel-alloy tubing has been extensively prepared by extrusion but only a limited amount of work has been reported on extruding the cobalt-base alloys. Forging has been extensively used not only to break down the ingot structure but also to produce closed-die forgings for final machining into parts at lower cost and with properties superior to those obtained by machining from wrought blocks. Most of the nickel- and cobalt-base alloys can readily be drawn into tube, rod, or wire.

The nickel- and cobalt-base alloys can be frequently formed by secondary deformation methods at room temperature. Extensive studies at Ling-Temco-Vought, Incorporated, for the U. S. Air Force have shown that the formability of sheet metal can be predicted from mechanical-property measurements obtained in simple tests. However, some of these property measurements are not readily available, and more or less special tests must be set up to obtain the required data. Reports of experience from several other industrial sources also have been compiled and summarized to offer assistance and guidance in performing many of the secondary deformation processes. More detailed information on any of the deformation processes is available by consulting the extensive list of references provided.

INTRODUCTION

The nickel-base alloys have found wide acceptance for corrosion-resistant applications in the marine and chemical-processing industries. Elevated-temperature applications brought about through the need for increasing efficiencies in aircraft propulsion systems, have spurred the development of new nickel-base and cobalt-base alloys. Rotor shafts, turbine blades, and compressor housings have demanded a continuing development of alloys with high strength at ever increasing temperature of service. Although most of the alloys were originally used as castings, some have been modified to permit production in wrought forms.

Most of the nickel-base and cobalt-base alloys can be worked at both room and elevated temperatures. The hot-working temperatures are generally higher than those used for steel because the materials retain their strengths to higher temperatures. The ductility of most alloys compares with stainless steels at room temperature so that secondary working can usually be carried out with conventional processing techniques.

The purpose of this report is to summarize the present status of deformation processes for nickel-base and cobalt-base alloys. Primary deformation processes are designed to reduce an ingot or billet to a standard mill product such as sheet or plate, bar, forging, and extruded or drawn rod, tube, or shape. Secondary metalworking processes produce semifinished or finished parts by additional forming operations on such primary shapes as sheet, bar, or tubing.

This report is based on information presented in a large number of technical publications and in reports on investigations sponsored by Government agencies. The source material is referenced so the reader can obtain more detailed knowledge by studying the pertinent publications. Additional information was collected by personal interviews with organizations currently concerned with fabrication of nickel-base and cobalt-base alloys.

NICKEL-BASE ALLOYS

In its pure state nickel is used primarily in corrosion-resistant applications. Nickel, with a face-centered cubic structure, has about the same strength as mild steel but is about 14 per cent heavier. Additions of chromium, molybdenum, tungsten, or cobalt result in solid-solution strengthening. Nickel alloys containing titanium and aluminum may also be strengthened by precipitation-hardening reactions. Most of the nickel-base alloys have good strength and ductility at both cryogenic and elevated temperatures up to 1600 F. The solid-solution-hardened alloys have the best creep resistance and are generally used at the higher temperatures. They cannot be heat treated, however, which limits their strength at room and slightly elevated temperatures. The precipitation-hardening alloys have strengths similar to low-alloy steels at room temperature. They lose their strength very rapidly at temperatures exceeding the aging temperature; most service applications have been limited to a temperature of 1400 F.

All of the nickel-base alloys have good oxidation resistance at elevated temperatures. Some combine good corrosion resistance with good elevated-temperature strength, which makes them very attractive for the chemical-processing industry. The nickel-base alloys, generally speaking, have good corrosion resistance in reducing acid environments, such as hydrochloric or sulfuric acid, but are corroded by oxidizing acids like nitric acid.

The composition and properties of commercially available nickel-base alloys are given in Table I. Producer's designations are given since only a small number of these alloys have been assigned specification numbers. The mechanical properties, given in Table II, should be considered nominal values at room temperature. Specific producers should be contacted for information on guaranteed properties.

HIGH-COBALT AND COBALT-BASE ALLOYS

Until recently, unalloyed cobalt had found few applications due to the poor ductility of the metallic forms obtained by conventional methods of preparation. Such impurities as lead, zinc, and sulfur have a significant effect on reducing the ductility. With the advent of new refining processes based on vacuum melting and casting as well as the development of powder-metallurgy techniques, the impurity level has been reduced so that ductile cobalt metal can now be produced.

Cobalt has about the same strength at room temperature as mild steel but is about 15 per cent heavier. Most of the cobalt-base alloys have approximately the same density as the nickel-base alloys.

TABLE I. NOMINAL CHEMICAL COMPOSITION OF REPRESENTATIVE NICKEL-BASE ALLOYS

Weight Per Cent.

Producer	Designation(a)	Ni	C	Mn	Fe	S	Si	Cu	Cr	Al	Ti	Mo	Co	Other
The International Nickel Company (Ref. 1)	Nickel 200 ("A" Nickel)	99.5	0.06	0.25	0.15	0.005	0.05	0.05	--	--	--	--	--	--
	Nickel 201 (Low-carbon nickel)	99.5	0.01	0.20	0.15	0.005	0.05	0.05	--	--	--	--	--	--
	Nickel 204	95.2	0.06	0.20	0.05	0.005	0.02	0.02	--	--	--	--	4.50	--
	Nickel 211 ("D" Nickel)	95.0	0.10	4.75	0.05	0.005	0.05	0.03	--	--	--	--	--	--
	Nickel 220	99.5	0.06	0.12	0.05	0.005	0.03	0.03	--	--	0.02	--	--	Mg 0.04
	Nickel 230	99.5	0.09	0.10	0.05	0.005	0.03	0.01	--	--	0.003	--	--	Mg 0.06
	Nickel 233 (330 Nickel)	99.5	0.09	0.18	0.05	0.005	0.03	0.03	--	--	0.003	--	--	Mg 0.07
	Nickel 270	99.98	0.01	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	--	<0.001	--	<0.001	Mg <0.001
	Monel 400 (Monel)	66.0	0.12	0.90	1.35	0.005	0.15	31.5	--	--	--	--	--	--
	Monel 401	44.5	0.03	1.70	0.20	0.005	0.01	53.0	--	--	--	--	0.50	--
	Monel 402	58.0	0.12	0.90	1.20	0.005	0.10	40.0	--	--	--	--	--	--
	Monel 403	57.5	0.12	1.80	0.50	0.005	0.25	40.0	--	--	--	--	--	--
	Monel 404	55.0	0.06	0.01	0.05	0.005	0.02	44.0	--	0.02	--	--	--	--
	Monel R-405 ("R" Monel)	66.0	0.18	0.90	1.35	0.050	0.15	31.5	--	--	--	--	--	--
	Monel 406 (LC Monel)	84.0	0.12	0.90	1.35	0.005	0.15	13.0	--	--	--	--	--	--
	Monel K-500 ("K" Monel)	65.0	0.15	0.60	1.00	0.005	0.15	29.5	--	2.80	0.50	--	--	--
	Monel 501 ("KR" Monel)	65.0	0.23	0.60	1.00	0.005	0.15	29.5	--	2.80	0.50	--	--	--
	Inconel 600 (Inconel)	76.0	0.04	0.20	7.20	0.007	0.20	0.10	15.8	--	--	--	--	--
	Inconel 604 (Inconel 600)	74.0	0.04	0.20	7.20	0.007	0.20	0.10	15.8	--	--	--	--	Cb 2.0
	Inconel 625	61.0	0.05	0.15	3.00	0.007	0.30	0.10	22.0	--	--	9.0	--	Cb 4.0
	Inconel 700	46.0	0.12	0.10	0.70	0.007	0.30	0.05	15.0	3.00	2.20	3.75	28.5	--
	Inconel 702	79.5	0.04	0.05	0.35	0.007	0.20	0.10	15.6	3.40	0.70	--	--	--
	Inconel 718	52.5	0.04	0.20	18.5	0.007	0.30	0.07	18.6	0.40	0.90	3.1	--	Cb 5.0
	Inconel 721 (Inconel M)	71.0	0.04	2.25	7.20	0.007	0.12	0.10	16.0	--	3.00	--	--	--
	Inconel 722 (Inconel W)	75.0	0.04	0.55	6.50	0.007	0.20	0.05	15.0	0.60	2.40	--	--	--
	Inconel X-750 (Inconel X)	73.0	0.04	0.70	6.75	0.007	0.30	0.05	15.0	0.80	2.50	--	--	Cb 0.85
	Inconel 751 (Inconel X-550)	72.5	0.04	0.70	6.75	0.007	0.30	0.05	15.0	1.20	2.50	--	--	Cb 1.00
	Incoloy 804 (Incoloy 804)	42.6	0.06	0.85	25.4	0.007	0.50	0.40	29.3	0.25	0.40	--	--	--
	Incoloy 825 (NI-O-NEL)	41.8	0.03	0.65	30.0	0.007	0.35	1.80	21.5	0.15	0.90	3.0	--	--
	Ni-Span-C 902	42.0	0.02	0.40	48.5	0.008	0.50	0.05	5.4	0.65	2.40	--	--	--
Haynes Stellite Company (Ref. 2)	Hastelloy B	61.0	0.05	1.0	4-7	--	1.0	--	1.0	--	--	26-30	2.5	--
	Hastelloy C	54.0	0.08	1.0	4-7	--	1.0	--	14.5-16.5	--	--	15-17	2.5	W 3-4.5
	Hastelloy F	48.0	0.05	1-2	13.5-17	--	1.0	--	21-23	--	--	5.5-7.5	2.5	Cb + Ta 1.7 - 2.5
	Hastelloy X	48.0	0.15	--	18.5	--	--	--	22	--	--	9	1.5	W 0.2-1
Kelsey-Hayes Company (Ref. 3)	R-235	61.0	0.16	0.25	10	--	--	--	16	2.25	2.5	5.5	2.5	--
	Udimet 500	Bal	0.15	0.75	4	--	0.75	--	15-20	2.5-3.2	2.5-3.2	3.5	13-20	--
	Udimet 600	50	0.10	--	4	--	--	--	18	4	3	4	17	--
	Udimet 700	53	0.15	--	1	--	--	--	15	4	3.5	5	18.5	--
	M-252	55.0	0.10	1	2	--	--	--	19	0.75	2.5	10	10	--
Henry Wiggin and Company Ltd. (Ref. 3)	Nimonic 75	77.4	0.10	0.45	0.50	--	0.45	--	20.5	0.15	0.35	--	--	--
	Nimonic 80A	74.5	0.05	0.55	0.55	--	0.20	--	20.45	1.25	2.40	--	--	--
	Nimonic 90	57.0	0.05	0.50	0.45	--	0.20	--	20.55	1.65	2.60	--	16.9	--

TABLE I. (Continued)

Producer	Designation[a]	Ni	C	Mn	Fe	S	Si	Cu	Cr	Al	Ti	Mo	Co	Other
General Electric Company (Ref. 4)	René 41	55.0	--	--	--	--	--	--	19	1.5	3.1	10	11	--
	René 62	48.0	--	--	22.5	--	--	--	15	1.25	2.5	9	--	Cb 2.25
	Astroloy	56.0	0.5	0.05	--	--	--	--	15	4.4	3.5	5.25	15	--
Carpenter Steel Company (Ref. 3)	Carpenter 901	43.0	0.10	2	32.5	--	--	--	12.5	0.35	3	6	--	--
Pratt & Whitney Aircraft (Ref. 3)	Waspaloy	Bal	0.10	0.5	2	--	0.75	--	18-21	1-1.5	2.7-3.2	3.5-5	12-15	--
Allegheny Ludlum Steel Corporation (Ref. 3)	D-979	Bal	0.05	0.6	27	--	--	--	15	1	3	4	--	W 4
Rolled Alloys Incorporated (Ref. 3)	RA-333	47	0.08	2	15	--	1	--	2.5	--	--	3.5	3.5	W 3.5
Universal-Cyclops Steel Corporation (Ref. 4)	Unitemp 1753	53	0.25	0.05	9.5	--	0.1	--	16.0	2.0	3.0	1.5	7.0	W 8.0

(a) Former material designation is shown in parentheses.

TABLE II. PHYSICAL CONSTANTS AND MECHANICAL PROPERTIES OF SELECTED ALLOYS (REF. 1)

Designation	Density, lb/in.^{3}	Modulus of Elasticity, 10^6 psi		Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Form and Temper	Previous Designation
		Tension	Torsion					
Nickel 200	0.321	30.0	11.0	67	21.5	47.0	Hot rolled, annealed	"A" Nickel
Nickel 201	0.321	30.0	11	50	10	40.0	Annealed	Low-carbon metal
Nickel 204	0.321	29.2	--	--	--	--	--	Nickel 204
Nickel 211	0.315	30.0	11	75	35	40.0	Annealed	"D" Nickel
Nickel 220	0.321	30.0	11	70	20	40.0	Annealed	220 Nickel
Nickel 230	0.321	30.0	11	70	20	40.0	Annealed	230 Nickel
Nickel 233	0.321	31.0	11	70	20	40.0	Annealed	230 Nickel
Nickel 270	0.321	30.0	--	46	8.5	30.0	Annealed	
Monel 400	0.319	26.0	9.5	79	30	48.0	Hot rolled, annealed	Monel
Monel 401	0.321	--	--	--	--	--	--	
Monel 402	0.320	--	--	65	23	35.0	Annealed	
Monel 403	0.320	25.0	--	65	23	35.0	Annealed	
Monel 404	0.321	25.0	9.4	--	--	--	--	"R" Monel
Monel R-405	0.319	26.0	9.5	70	25	35.0	Annealed	"LC" Monel
Monel K-500	0.306	26.0	9.5	97	49	44.0	Hot rolled	"K" Monel
Monel 501	0.306	26.0	9.5	95	45	35.0	Annealed	"KR" Monel
Inconel 600	0.304	31.0	11.0	90.5	36.5	47.0	Hot rolled, annealed	Inconel
Inconel 604	0.305	31.0	--	125	--	--	--	Inconel 600
Inconel 625	0.305	29.8	11.4	142	86	42.0	Hot rolled, annealed	
Inconel 700	0.295	32.0	--	170	105	25.0	Aged	
Inconel 702	0.302	32.0	--	105	45	55.0	Annealed	

TABLE II. (Continued)

Designation	Density, lb/in.^{3}	Modulus of Elasticity, 10^6 psi		Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Form and Temper	Previous Designation
		Tension	Torsion					
Inconel 718	0.296	29.0	11.2	211	174	23.0	Aged	
Inconel 721	0.298	31.0	11	110	45	50.0	Annealed	Inconel "M"
Inconel 722	0.298	31.0	11.0	165	99	31.0	Aged	Inconel "W"
Inconel X-750	0.298	31.0	11.0	162.5	92.5	22.0	Heat treated	Inconel "X"
Inconel 751	0.298	31.0	11.0	125	75	50.0	Annealed	Inconel "X-500"
Incoloy 804	0.286	28.0	--	--	--	--	--	
Incoloy 825	0.294	28.0	--	90.5	35.1	50.0	Hot rolled, annealed	NI-O-NEL
Ni-Span-C 902	0.293	24-29	9-10	90	35	40.0	Solution annealed	
Hastelloy B	0.334	26.5	--	80	50	8	Rolled	(Ref. 2)
Hastelloy C	0.323	30.9	--	130	71	45	Rolled	Ditto
Hastelloy F	0.295	--	--	103	45	46	--	"
Hastelloy X	0.297	28.6	--	113	52	41	Annealed	"
R-235	--	--	--	159	100	27	--	
Udimet 500	--	31.0	--	195	125	12	Heat treated	(Ref. 3)
Udimet 600	--	--	--	235	200	20	Heat treated	Ditto
Udimet 700	--	31.0	--	203	140	18	Heat treated	(Ref. 4)

TABLE II. (Continued)

Designation	Density, lb/in.^{3}	Modulus of Elasticity, 10^6 psi: Tension	Modulus of Elasticity, 10^6 psi: Torsion	Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Form and Temper	Previous Designation
M-252	--	--	--	179	110	20	--	
Nimonic 75	0.302	27.0	--	115	55	40	Annealed	(Ref. 4)
Nimonic 80A	0.296	31.0	--	115	60	60	Annealed	Ditto
Nimonic 90	0.298	31.0	--	155	90	--	Annealed	"
René 41	0.298	12.1	--	180	135	9	Aged	"
René 62	--	--	--	212	164	9	Aged	"
Waspaloy	0.295	31.4	--	185	115	25	Forged	"
Astroloy	--	--	--	178	123	22	--	"
Carpenter 901	--	29.9	--	165	108	23	--	"
D-979	--	--	--	185	132	13	--	
RA-333	--	--	--	108	50	43	--	

TABLE III. NOMINAL CHEMICAL COMPOSITION OF REPRESENTATIVE COBALT-BASE ALLOYS (REF. 4)

Weight Per Cent.

Producer	Designation	Ni	C	Mn	Fe	S	Si	Cu	Cr	Al	Ti	Mo	Co	Other
Haynes Stellite Company	Haynes Stellite 21	1.5-3.5	--	1	2	--	--	--	25-30	--	--	4.5-6.5	Bal	--
	Haynes Stellite 25	9-11	0.1	1-2	3	--	--	--	19-21	--	--	--	Bal	W 14-16
Westinghouse Electric Corporation	Refractory 70	19-21	--	1.75 2.25	12 20	--	--	--	19-21	--	--	7.8 8.5	28.5 31.5	W 3.5 4.5
	Refractory 80	19-21	--	0.5 2.0	16	--	--	--	19-21	--	--	9-11	28.5 31.5	W 4.5 5.5
	Nivco-10	21.5 23.5	--	--	1	--	--	--	--	--	1.5 2.0	--	Bal	Zr 0.45 0.80
General Electric Corporation	J-1570	28	--	--	2	--	--	--	20	--	4	--	Bal	W 7
	J-1650	27	--	--	--	--	--	--	19	--	3.8	--	Bal	W 12 Ta 2
	X-63	10	0.4 0.5	0.5	3	--	--	--	25	--	--	6	Bal	--
Allegheny Ludlum Steel Company	V-36	20	0.3	1	3	--	--	--	25	--	--	4	42	W 2 Cb 2
	S-816	20	0.4	1.2	3	--	--	--	20	--	--	4	43	W 4 Cb 4
Crucible Steel Company	WF-11	9-11	0.15	1-2	--	--	--	--	19-21	--	--	--	Bal	W 14-16
Jessop Steel Company	Saville G-32	12-13	--	--	16	--	--	--	18.7 19.5	--	--	1.9 2.1	Bal	V 2.7-2.9 Cb 1.2-1.4
Universal-Cyclops Steel Corporation	Unitemp L-605	Same composition as Haynes Stellite 25												

TABLE IV. PHYSICAL CONSTANTS AND MECHANICAL PROPERTIES OF COBALT-BASE ALLOYS

Designation	Density, lb/in.^{3}	Modulus of Elasticity, 10^6 psi		Tensile Strength, 10^3 psi	Yield Strength, 10^3 psi	Elongation, per cent	Form and Temper	Reference
		Tension	Torsion					
Hastelloy 21	0.299	16.8	--	--	--	--	--	5
Hastelloy 25	0.333	35.0	--	145	65	55	--	5
Refractory 70	0.313	--	--	132	87	3	--	5
Refractory 80	0.320	34.0	--	162	102	2	--	5
J-1570	0.305	33.5	--	132[a]	84[a]	12[a]	--	5
J-1650	--	34.1	--	206	148	27	--	5
V-36	0.303	32.4	--	145	67	55	--	6
S-816	0.313	35.0	--	140	72	35	--	6
WF-11	0.333	35.0	--	155	70	55	--	5
Nivco-10	0.312	30.5	--	165	110	25	--	5
Saville G-32	--	--	--	148	102	8	--	5
Unitemp L-605	0.333	35.3	--	160	85	47	--	5

(a) Properties at 1200 F.

There are two allotropic modifications of cobalt: a close-packed hexagonal form stable at temperatures below 417 C (785 F) and a face-centered cubic form, alpha, stable at higher temperatures. Due to the sluggishness of the transformation upon cooling from high temperature, a two phase structure is often found (Ref. 5). Additions of most of the common alloy elements such as columbium, nickel, iron, and aluminum depress the temperature at which the transformation will take place. The addition of chromium, on the other hand, increases the transformation temperature. Most alloys of cobalt have an adjusted chemistry to give an alpha or face-centered cubic structure at room temperature. The additions of nickel and chromium are generally balanced to counteract their individual effects on the transformation temperature.

For most deformation processing, the alpha structure is desirable because it exhibits better ductility than the hexagonal, close-packed crystal structure. Elimination of the transformation also simplifies using the alloys at elevated temperatures. Most structural applications would necessitate heating and cooling the alloys through the transformation if it were permitted to occur at 785 F.

The chemical compositions of some commercially available cobalt-base alloys are given in Table III. Alloy specification numbers and producer's designations are included for reference. The mechanical properties for these alloys are given in Table IV. The values are generally considered as nominal at room temperature; specific producers should be contacted for information on design minimums and guaranteed properties.

PRIMARY DEFORMATION PROCESSES

This section of the report describes fabrication procedures for the rolling, forging, extrusion, and drawing of wrought nickel-base and cobalt-base alloys. Table V lists the available mill-product forms for the major alloy compositions.

Due to the wide range of compositions in these two alloy systems, the workability of these alloys and the mill practices vary considerably. Since the details are of minor interest to most readers, only general descriptions of the processing practices are presented in this section.

TABLE V. AVAILABLE MILL FORMS OF NICKEL-BASE AND COBALT-BASE ALLOYS (REFS. 1,2,4,6)

Alloy	Sheet	Strip	Plate	Rod and Bar	Rolled Shapes	Extrusions	Forgings	Tubing	Wire
				Nickel-Base Alloys					
Monel 400	x	x	x	x	x	x	x	x	x
Monel K-500	x	x	x	x	--	x	x	x	x
Inconel 600	x	x	x	x	x	x	x	x	x
Inconel 700	--	--	--	x	--	--	--	--	--
Inconel 718	x	x	x	x	--	x	x	x	--
Inconel X-750	x	x	x	x	--	x	x	x	x
Incoloy 901	x	--	--	x	--	--	--	--	--
Hastelloy B	x	x	x	x	--	--	x	x	x
Hastelloy C	x	x	x	x	--	--	x	x	x
Hastelloy X	x	x	x	x	x	--	x	x	x
Hastelloy R-235	x	x	x	x	--	--	x	x	x
Udimet 500	x	x	x	x	--	--	--	--	--
Udimet 700	--	--	x	x	--	--	--	--	--
Waspaloy	x	x	x	x	x	--	--	x	x
René 41	x	x	x	x	--	--	x	--	x
Nimonic 75	x	x	--	x	--	x	--	x	--
M-252	x	x	--	x	--	--	x	--	x
Unitemp 1753	x	x	--	x	--	--	x	--	x
TD Nickel	x	x	x	x	--	x	x	x	x
				Cobalt-Base Alloys					
J-1650	x	x	--	x	--	--	--	--	x
S-816	x	--	--	x	--	--	--	--	x
U-36	x	--	--	x	--	--	x	--	x
Haynes 25; L-605	x	x	x	x	x	--	--	x	x
Stellite 6B	x	x	x	x	--	--	--	--	--
Stellite 6K	x	x	x	x	--	--	--	--	--
Nivco	x	x	x	x	--	--	x	--	x

ROLLING

Rolled products, particularly sheet, plate, and rod, are available in nickel- and cobalt-base alloys and comprise the biggest market for these alloys in aircraft and aerospace applications. Except for rod coils for subsequent wire fabrication, rolled products are generally supplied in flat or straight sections.

Classification of Rolling Processes. The rolling operation combines both compressive and tensile forces to reduce the cross section of plastic metal, to change its shape, or both. This combination of rolling forces deforms the metal symmetrically about a neutral plane, parallel to the surface, distorting the grain structure. Cylindrical rolls produce flat products – grooved rolls produce rounds, squares, and structural shapes.

The terms hot rolling and cold rolling as used in this report denote processing above or below the recrystallization temperature, respectively. Little or no strain hardening occurs in hot rolling; considerable work hardening occurs in cold rolling. Rolling develops directional mechanical properties and heavily worked grain structures.

Rolling Equipment. Detailed information on the design and operation of steel mill rolling equipment is available elsewhere (Ref. 7) so that only a brief discussion of equipment and rolling nomenclature is provided here as a basis for the process descriptions provided in the report.

Figure 1 shows the most common mill designs used in rolling. The reversing two-high and three-high mills are commonly used for breakdown and semifinishing operations in the fabrication of both flat products and shapes. Single-stand two-high mills are reversible so that the workpiece can be deformed while traveling in either direction. Heavy pieces and long lengths can be handled conveniently on this type mill for fabrication of slabs, blooms, plates, billets, rounds, and partially formed sections. The three-high mill does not require any drive reversal as the direction of rolling depends upon whether the piece is traveling above or below the center roll. This type of mill is generally used for products other than plate or sheet.

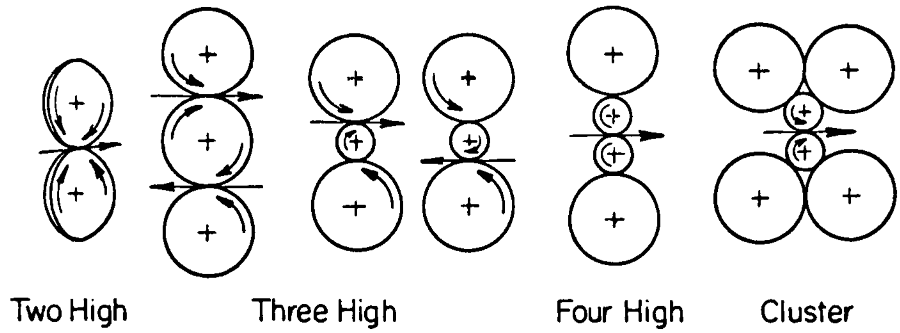


FIGURE 1. TYPICAL ROLLING-MILL DESIGNS

For rolling of narrow material where thickness control is not too critical, the two-high and three-high rolling mills described above are adequate. For rolling of wide material, four-high mills are used to achieve better roll rigidity and closer thickness control. Four-high mills are used for producing both hot- and cold-rolled plate and sheet. Several of these mills are used in tandem for continuous rolling of sheet.

The cluster mill is used for rolling very thin sheet or strip where very close thickness control must be maintained.

Fabrication of Rolled Products. In many ways, the rolling procedures for nickel-base and cobalt-rich alloys are similar to those used for titanium. A number of important similarities exist, such as the need for frequent surface conditioning during processing, close control of working temperatures, and small reductions per pass in initial breakdown operations.

Ingot Breakdown. After solidification, the cast ingots (weighing up to 10,000 pounds) are removed from the mold and immediately placed in a soaking furnace for heating to the proper forging temperature. All ingots are forged before rolling to break down the cast structure. The hot-working range is very narrow for both the nickel-base and cobalt-base alloys so that frequent reheating is necessary during the ingot breakdown – as many as 30 times may be necessary depending upon the billet size and the alloy composition.

Ingots to be used for sheet or plate processing are forged to rectangular slabs. If the final product is to be in bar form, ingots are forged to squares. Round shapes in diameters of 3-1/2 inches and up to 16 inches are also forged. These forged rounds may then be cut to provide pancakes for forging in closed dies.

After forging, billets are surface conditioned and the hot-topped end is removed. Generally, forged material is ultrasonically inspected at this point.

Rolling of Flat Products. Forged slabs are hot rolled on three-high mills down to 3/8-inch-thick plate. Slabs are frequently cross rolled to reduce directionality. As indicated previously, the narrow hot-working range requires numerous reheatings. Surface conditioning is also a frequent operation between rolling passes. At this point in the processing, material is pickled and shot blasted before further rolling.

Below the 3/8-inch-plate thickness, all rolling is done on a two-high mill down to 0.045-inch sheet. The sheet may be finished hot or cold. Cold rolling enhances the mechanical properties and provides closer control of the sheet thickness. Further rolling to an 0.008 to 0.010-inch minimum sheet thickness and up to 36 inches in width is usually done cold on a Sendzimir mill.

Rolling of Bar Products. Typical fabrication schedules for these alloys involve hot rolling of the forged bars down to 2-1/4-inch gothics on a 24-inch mill, followed by surface conditioning and reheating for rolling on a 10-inch mill down to 5/16-inch-diameter rod. Rod intended for wire production is coiled at this size for further processing by cold drawing into wire as small as 0.001 inch in diameter.

Post-Fabrication Processing. Hot-rolled sheet and plate are generally heat treated after rolling and then descaled in a hot caustic bath. Following this, the material is pickled in a hot, strong acid to give a smooth bright finish. Plate is flattened by roller leveling and then sheared to finish size. Sheet products are stretch straightened and cut to size.

Bar products over 2-1/4 inches in diameter are generally straightened, heat treated, and ground to finish size. Smaller diameter bars are straightened, ground, heat treated, descaled, and pickled prior to coiling.

Sizes and Tolerances of Rolled Products. The classification as "sheet", "strip", or "plate" is dependent upon the relationships between width and thickness of the products. The distinction between the three for nickel- and cobalt-base alloys can be generally defined as follows:

Product	Dimensions, inches	
	Width	Thickness
Plate	Greater than 10	Greater than 0.250
Sheet	Greater than 12-14	Less than 0.250
Strip	Less than 12-14	Less than 0.250

Plate. The sizes of plates available vary considerably among the alloys in question. Several alloy types are listed below along with their plate-size capabilities:

Alloy	Plate Sizes Available, inches		
	Thickness	Width	Length
Monel	3/16 - 4	10-150	600
Inconel	1/4 - 4	10-150	120-160
Hastelloy-Haynes 25	3/16 - 2	30-54	132
Stellite	3/16 - 1	36	120
Udimet	1/8 - 1-1/2	--	--

Thickness tolerances on plate are listed below:

Nominal Thickness, inches	Thickness Tolerances, inch
3/16	+0.021 -0.010
1/4	+0.027 -0.010
1/2	+0.035 -0.010
3/4	+0.045 -0.010
1 to 1-1/2	+5 per cent -0.010
1-1/2 to 2-1/2	+5 per cent -0.010

Flatness tolerances of 1/4 to 3/8 inch can be met on plate widths of 48 inches or less.

Sheet, Strip, and Foil. The nickel-base alloys generally are available in sheet thicknesses down to 0.018 inches, widths of 44 to 60 inches, and lengths up to 144 inches (Refs. 8,9). The Stellite cobalt-base alloys are restricted to somewhat smaller widths and lengths, 12 to 48 inches, and 48 to 120 inches, respectively (Ref. 9). TD nickel is available in sheet sizes of 0.030 to 0.075 x 24 x 92 inches (Ref. 10).

Generally speaking, any of the sheet sizes can be slit into strip of any desired width.

Typical thickness tolerances for nickel-base and cobalt-base-alloy sheet are listed below:

Nominal Thickness, inch	Thickness Tolerance, inch
0.017-0.025	±0.003
0.028-0.038	±0.004
0.044-0.056	±0.005
0.078	±0.007
0.109	±0.009
0.141	+0.016 -0.010
0.172	+0.018 -0.010

Flatness tolerances vary from 1/8 to 1/4 inch, depending upon the alloy, in sheet widths up to 48 inches.

Aerospace applications for foil materials are becoming very important and many of the superalloys can be supplied in foil thickness of 0.001 to 0.004 inch and widths of 24 inches (Ref. 11). A thickness tolerance of 5 per cent is easily met; a 2 per cent tolerance can be met in many cases. René 41, Inconel, Haynes 25, and TD nickel alloys have all been supplied in foil form.

In strip form (4 to 12 inches wide) many alloys have been rolled to thicknesses of 0.0003 inch (Ref. 12).

Rolled Rod and Bar. Hot-finished rod and bar is available in rounds, squares, and hexagons in diameters from 1/4 inch to 12 inches and lengths up to 24 feet. Again, sizes vary considerably with the particular alloy. Rod diameters up to 3 to 4 inches are available in nearly all alloys.

The fabrication of rolled shapes such as angles, tees, and airfoil shapes has been extensive. Figures 2 and 3 show some typical rolled shapes that have been fabricated in lengths up to 30 feet. Size limitations and tolerances for precision-rolled shapes as reported by Universal Cyclops (Ref. 13) are shown in Figure 4.

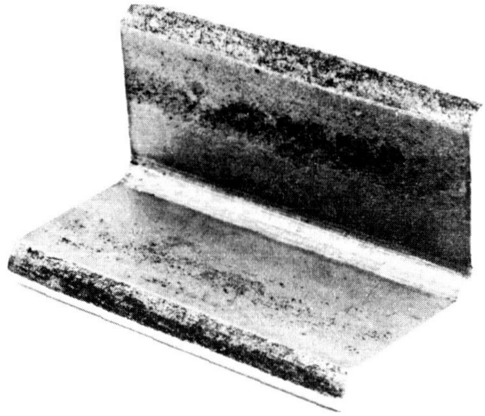


FIGURE 2. ROLLED ANGLE OF L-605 COBALT-BASE SUPERALLOY WITH LEGS OF EQUAL LENGTH

Courtesy of Allvac Metals Company, Monroe, North Carolina.

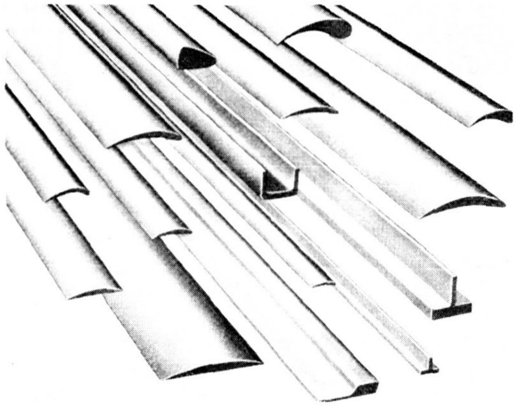


FIGURE 3. TYPICAL ROLLED SHAPES FABRICATED FOR JET AND GAS-TURBINE ENGINES

Courtesy of D. E. Makepeace Division, Englehard Industries, Inc., Attleboro, Massachusetts.

EXTRUSION

The extrusion process has been used extensively in the production of seamless tubing, particularly for the Monel and Inconel alloys. Simple shapes, such as engine rings, have been extruded in a variety of nickel-base alloys, but only a limited amount of work on extrusion of cobalt-base alloys has been reported. An extrusion program for producing superalloys in structural shapes has just been initiated at TRW Inc. (Ref. 14). Allegheny-Ludlum (Ref. 15) has started an internal research program to develop extrusion techniques for producing L-605, Waspaloy, and N-155 alloy rounds, squares, rectangles, and tubing.

Extrusion is also used as a breakdown operation on materials with large as-cast grain sizes (Ref. 16). Alloys that are prone to crack during rolling or forging of the cast ingot are extruded at a 5 to 10:1 extrusion ratio to break up the cast structures and provide a round or rectangular section for forging or rolling. The

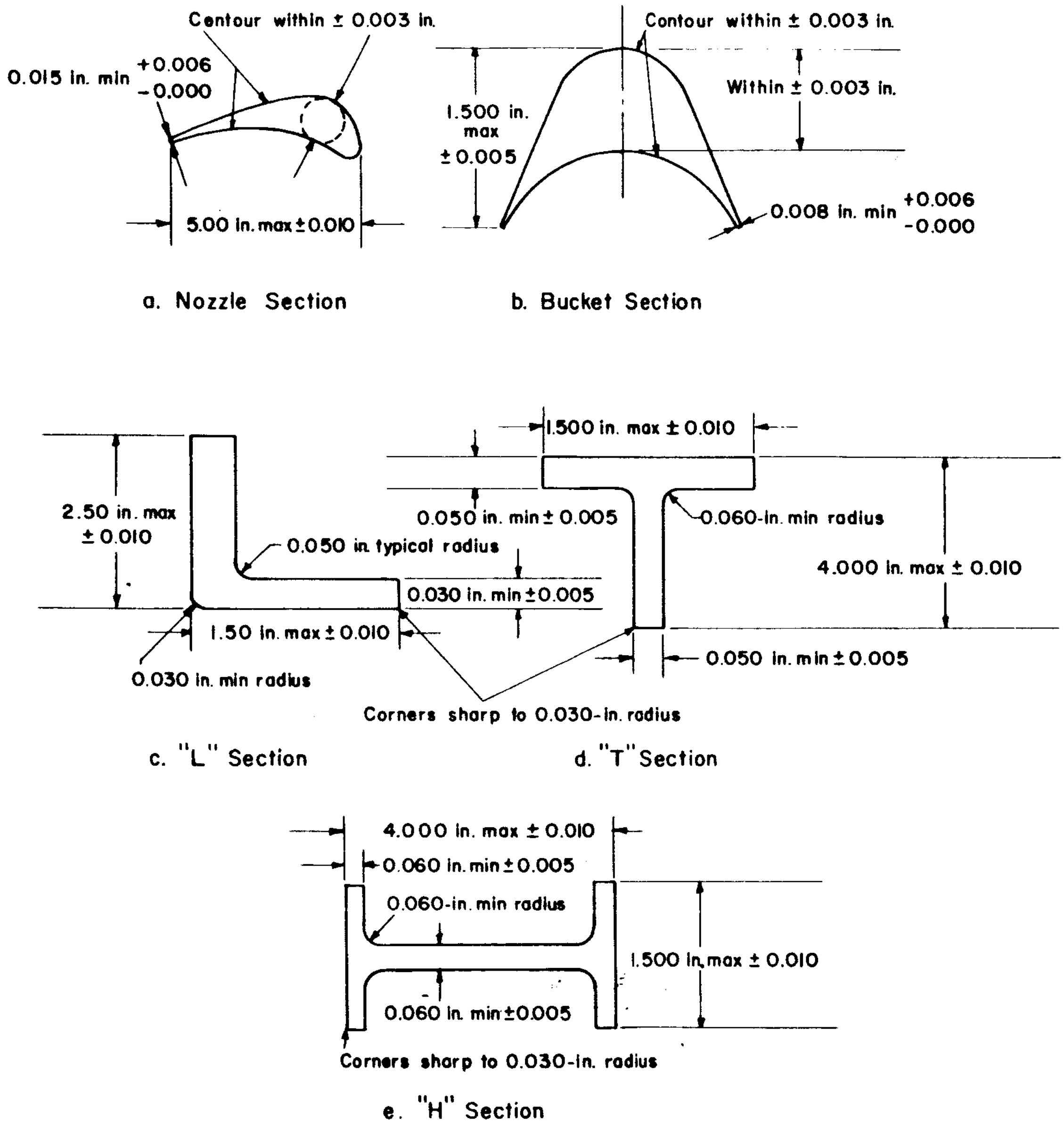


FIGURE 4. SIZE AND TOLERANCE LIMITATIONS ON PRECISION-ROLLED SHAPES (REF. 13)

compressive stresses characteristic of extrusion minimize cracking during hot working.

Techniques for extrusion of these alloys are very similar to steel-extrusion practices. The use of the Ugine-Sejournet glass-lubrication process has made the extrusion of some of these alloys a commercial possibility at extrusion ratios up to 60:1.

Classification of Extrusion Processes. In the extrusion process, the billet is forced under compressive stress to flow through the opening of a die to form a continuous product of a smaller and uniform cross-sectional area. The process can be used to produce rounds, shapes, tubes, hollow shapes, or cups.

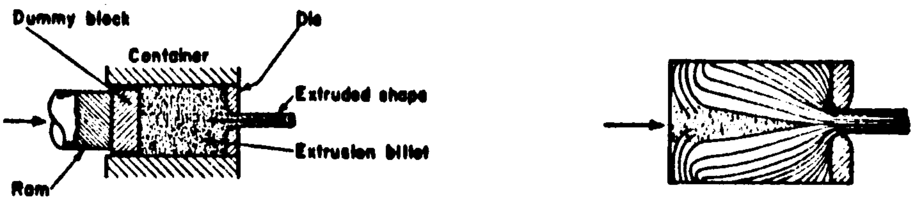
The most common method of extrusion is referred to as "direct" extrusion. In this technique, the ram moves through the container to force the billet material through a stationary die. The ram, billet, and extrusion all move in the same direction. In the "indirect" or "inverted" method of extrusion, a hollow ram and die move against a stationary billet causing the billet material to flow in an opposite direction through the die and ram. These processes are shown schematically in Figure 5, which includes diagrams illustrating methods for tube extrusion (Ref. 17).

The indirect process requires lower pressures for extrusion since friction between the container and the billet is largely eliminated. The actual use of the process is not widespread, however, because of other limitations.

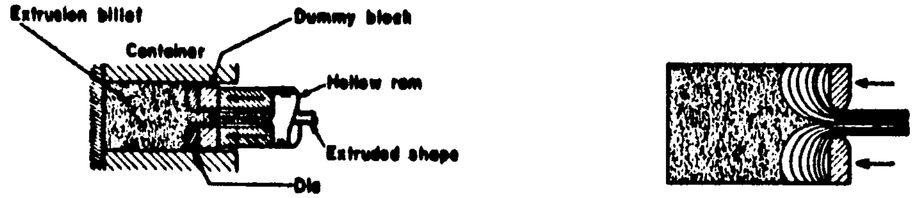
Extrusion Equipment and Tooling. The application of force to the billet by a ram is actuated hydraulically or mechanically. Hydraulic presses are driven directly by high-pressure oil pumps or by hydropneumatic accumulators. Mechanical presses utilize the energy of electrically driven fly wheels.

Horizontal Presses. Horizontal presses are ordinarily used for hot-extrusion operations and are available with capacities up to 14,000 tons. The largest presses of this kind were built as a result of the U. S. Air Force heavy-press program. Presently in the United States, there are nine of these heavy presses, ranging in capacity from 8,000 to 14,000 tons. The largest press equipped for titanium extrusion has a capacity of 12,000 tons.

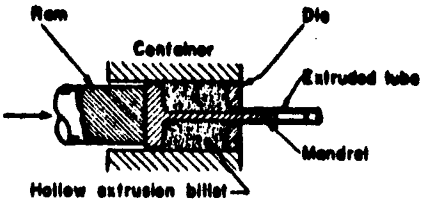
The selection between pump-driven or accumulator-driven presses is primarily governed by the press capacity and the material



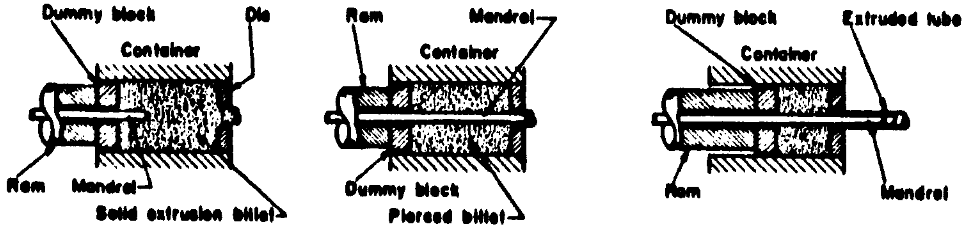
a. Direct Extrusion of a Rod or Shape



b. Indirect or Inverted Extrusion



c. Extrusion of a Tube From a Hollow Billet



d. Extrusion of a Tube From a Solid Billet

FIGURE 5. DIAGRAMMATIC REPRESENTATION OF DIFFERENT TYPES OF EXTRUSION PROCESSES (REF. 17)

being extruded. On the basis of press capacity only, the choice is one of economy. Direct-drive pumping systems are usually more economical for comparatively small presses (Ref. 18), and accumulators are used only where high ram speeds are necessary. For large presses of high capacity, e.g., 4000 tons or more, economy generally favors accumulators whether high speeds are required or not. Thus, all of the heavy presses are driven by accumulator systems even though the ram-speed capabilities range from about 50 inches per minute to over 700 inches per minute.

When materials are taken into consideration, then the ram-speed requirement becomes a deciding factor in press selection. High ram speeds are required in high-temperature extrusion to minimize heat transfer from the billet to the tools. This problem becomes increasingly critical at the higher billet temperatures required for superalloys.

Vertical Presses. Vertical presses are preferred for producing small-diameter, thin-wall tubes. The design simplifies the solution to problems of alignment of tooling and securing fast production rates. The maximum capacities of such presses usually range from 650 to 2400 tons. The larger presses are also used for cold extrusion and operations resembling hot forging.

High-Energy-Rate Machines. Pneumatic-mechanical machines, powered by compressed gases, have also been used for extrusion (Ref. 19). The capacity of such equipment, controlled by the kinetic energy of the moving piston and ram, ranges up to 1.5 million foot-pounds. Striking velocities range up to 3600 inches per second. The high speed permits deformation under essentially adiabatic conditions and minimizes the time available for heat loss from the billet to the tooling.

However, the use of high impacting speeds has an adverse effect on tool life and results in unusually high exit speeds. Sometimes the extrusion product is ruptured by the inertial force. A number of approaches have been tried, with limited success, for slowing down the extrusion product of high-energy-rate machines.

<u>Extrusion Practices</u>. The hot-extrusion process is employed for the production of long sections. All extruders employ the Sejournet glass process, using procedures similar to those developed for extruding steel. The use of glass as an extrusion lubricant, as in the Ugine-Sejournet hot-extrusion process, was originally developed by the Comptoir Industriel d'Etirage et Profilage de Metaus,

Paris, France, for extruding ferrous materials. As glasses were found that could be employed over a wide range of temperatures, the process was adopted for titanium, superalloys, refractory metals, and other metals.

The practices employed by the American licensees of the glass process for extruding nickel- and cobalt-base alloys are essentially identical. Billets are transferred from the heating furnace to the charging table of the extrusion press. As a billet rolls into position in front of the container, it passes over a sheet of glass fiber or a layer of glass powder that fuses to the billet surface. In addition, a fibrous glass pad is placed in front of the die, providing a reservoir of glass at the die face during extrusion.

For tubes, either a fibrous-glass sock is placed over the mandrel or powdered glass is sprinkled on the inside surface of the hollow billet.

Besides providing effective lubrication, glass serves as an insulator to protect the tools from contact with the hot billet during extrusion. Excessive overheating of tools does not occur, tool life is increased, and die costs are reduced.

Billet heating may be done in either gas- or oil-fired furnaces, by induction, or by salt-bath heating (Ref. 16). Due to the low thermal conductivity of the nickel-base and cobalt-rich alloys, fairly long induction-heating times are required to insure uniform heating of the extrusion billet.

The keys to the successful extrusion of these alloys are accurate temperature control and working within a narrow temperature range. Thus, transfer times between the furnace and the extrusion press must be minimized to prevent heat loss. Also, the speed of extrusion must be controlled so that overheating does not result from the heat of deformation that is generated during extrusion.

Canning of the superalloy billets in other metals has shown promise in work at Allegheny-Ludlum (Ref. 15) for successfully extruding an Astroloy round as shown in Figure 6. Curtiss-Wright also reported that canning was desirable for Astroloy and Udimet 700 alloy extrusions (Ref. 16). After extrusion, the cladding material is removed by machining or chemical attack.

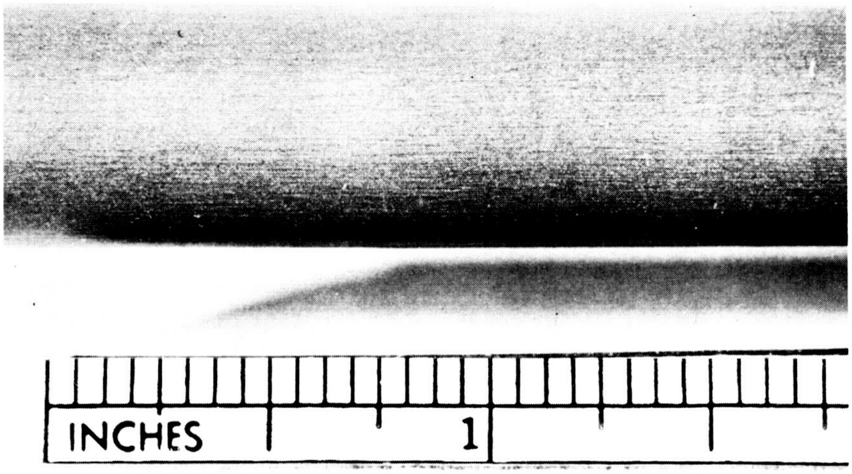


FIGURE 6. SECTION OF EXTRUDED ASTROLOY ROD (REF. 15)

Extrusion ratio of 30:1.

Post-Extrusion Processing. Whenever possible, the extruded product is quenched after extrusion to remove any adhering glass. Quenching also prevents hardening by precipitation in some metals. However, air cooling may be required if the extruded cross-sectional area is large or if the alloy is sensitive to quench cracking.

Extrusion products usually require detwisting or straightening on hydraulic torsional stretchers or roll straighteners.

Size Limits. Monel and Inconel extruded tubing is available in "as extruded" and "as extruded and pickled" forms with wall thicknesses ranging from 1/4 to 1 inch and outside diameters varying from 2-1/2 to 9-1/4 inches. Large tubing is available in lengths up to 15 feet; smaller sizes can be supplied in lengths up to 30 feet.

The limited amount of superalloy extrusion that has been done to date precludes any presentation of size capabilities. As related to aerospace applications, this specific area is yet to be developed.

FORGING

Nickel-Base Alloys. Today wrought nickel-base alloys can be used in applications at temperatures up to 1800 F because fabrication techniques have improved in stride with the increased knowledge of the strengthening mechanisms. Vacuum-melting techniques now in production reduce the level of the gaseous elements that contribute to poor workability. Metalworking knowledge has also improved to the extent that more complex shapes can be forged and closer tolerances can be held. Nickel-base alloys can be categorized according to their technique of hardening:

(1) Solid-solution hardening

(2) Precipitation hardening

(3) Complex hardening derived from small boron and zirconium additions.

A brief description here is important to understanding the forging behavior of nickel-base superalloys (Ref. 20). Compared with steel, such alloys have poor forgeability from the standpoints of ductility, pressure requirements, and permissible temperature ranges.

Solid-solution hardening of nickel results from the presence of elements such as chromium, molybdenum, and tungsten in the composition. These elements are soluble and contribute to the strength of the homogeneous single-phase alloy when completely dissolved. Thus, the minimum hot-working temperatures of the alloys are necessarily raised over that of nickel, but forgeability is not impaired.

Precipitation hardening results from the formation of compounds and phases from additions of carbon, aluminum, titanium, and columbium to the composition of the nickel alloy. These elements are only partially soluble at hot-working temperature but dissolve completely at higher temperatures. To achieve high strength the alloys are quenched from the solution-heat-treatment temperature and then aged. The aging treatment that improves strengths at high temperatures is usually carried out at temperatures between 1400 and 2000 F. For a particular alloy the proportion and composition of precipitate can be controlled by the aging temperature.

Generally an increase in quantity of carbide precipitated at the grain boundary reduces the forgeability and adds to the strength of the alloy. The precipitation reaction is accelerated by strain; therefore, it is possible for precipitates to form during forging operations. This type of hardening during hot deformation is a strain-induced precipitation reaction not an indication of work hardening.

Gamma prime [$Ni_3(Al,Ti)$] is a phase in nickel-base superalloys that develops with increasing amounts of aluminum. The effect of gamma prime is to increase the tensile strength of the alloy at elevated temperatures, but at the expense of forgeability. Cobalt additions reportedly stabilize gamma prime and carbides by raising the temperature at which they become soluble. The forgeability is directly impaired with cobalt additions.

Small additions of boron and zirconium have a hardening effect on nickel-base alloys. It is believed that these elements fill the lattice vacancies normally present at or near the grain boundaries and prevent carbide precipitation at those locations. In amounts ranging around 0.01 per cent boron or 0.07 per cent zirconium, such additions are beneficial to forgeability; however, over this quantity required to fill the vacancies at the grain boundaries, these additions reduce the forgeability.

The forging temperature of nickel-base alloys is limited on the high side by melting and on the low side by the precipitation reactions. As the forging temperature range is narrowed, not only does the process control become more difficult, but the general forgeability is reduced. The forging-temperature range of some nickel-base alloys is shown in Table VI.

Some forgeability characteristics of nickel-base superalloys can be measured in hot-tensile tests. Typically the ductility decreases in the temperature range where precipitation occurs and improves where precipitates become soluble. In Table VII the alloys are listed in approximately the order (decreasing) of the tensile ductility at temperatures in the middle of the suggested range for forging. Figure 7 illustrates some typical elevated-temperature short-time tensile-elongation relationships.

Forgeability of nickel-base superalloys decreases as the rate of deformation increases. Normally this is a consequence of overheating by the closer approach to adiabatic deformation characteristics of fast strain rates. A study conducted at Lockheed Aircraft Corporation (Ref. 21) used a high-energy-rate forging machine to deform samples by upsetting at rapid rates. At some intermediate temperatures, increasing the rate of deformation resulted in larger reductions for a constant amount of energy. Nevertheless, cracking occurred when the upset reduction exceeded 50 per cent. Presumably the work of deformation heated the samples enough to cause melting in some regions.

TABLE VI. CRITICAL MELTING AND PRECIPITATION TEMPERATURES FOR SEVERAL NICKEL-BASE SUPERALLOYS (REF. 21)

Alloy Designation	Approximate Temperature, F		Estimated Forging Temperature Range, F	
	First Melting	Precipitation	Maximum	Minimum
Hastelloy X	2300	1400	2250	1500
Inconel 718	2300[a]	1550	2200	1600
Waspaloy	2250[a]	1800	2200	1750
Incoloy 901, Al 901, Altemp 1251, Udimet 200	2200	1800	2150	1750
Inconel X-750	2350[a]	1750	2200	1800
M-252	2200[a]	1850	2150	1750
Hastelloy R-235, Unitemp R-235	2300	1900	2200	1850
René 41, Haynes R-41, Altemp R-41, Udimet R-41	2250	1950	2200	1900
Udimet 500, Unitemp 500, Hastelloy 500, Allvac 500	2250	2000	2200	1950
Udimet 700	2250[a]	2050	2200	1950
Astroloy	2250[a]	2050	2200	2000

(a) Estimated from data provided by producers.

TABLE VII. EMPIRICAL FORGEABILITY RATINGS FOR SEVERAL NICKEL-BASE SUPERALLOYS BASED ON LIMITING TEMPERATURES FOR FORGING AND TENSILE DUCTILITY (REF. 21)

Alloy	Limiting Forging Temperatures, F (Based on Melting and Precipitation)		Factor for Temperature Range[a]	Approximate Tensile Elongation at Forging Temperatures		Factor for Ductility[b]	Forgeability Rating[c]
	Maximum	Minimum		Temperature, F	Elongation, per cent		
Hastelloy X	2250	1500	7.5	1900	40-45	4.5	12.0
Inconel 718	2200	1600	6.0	2000	>100	10.0	16.0
Inconel 901	2150	1750	4.0	1800	70-75	7.5	11.5
Waspaloy	2200	1750	4.5	2000	>40	5.0	9.5
Hastelloy R-235	2200	1850	3.5	2000	55-60	6.0	9.5
René 41	2200	1900	3.0	2000	15-20	2.0	5.0
Udimet 500	2200	1950	2.5	2000	25-30	3.0	5.5
Udimet 700	2200	1950	2.5	2000	25-30	3.0	5.5

(a) The factor for forging temperature is considered to be 1/10 the permissible range for forging as expressed in degrees Fahrenheit.

(b) The ductility factor is taken as 1/10 the elongation value in hot-tensile tests at temperatures near the middle of the forging range. The maximum value is 10 on this scale.

(c) Forgeability rating is the sum of factors for temperature range and ductility.

The effect of forging temperature on the mechanical properties and microstructure of Waspaloy was investigated by Wyman-Gordon Company (Ref. 22). In the range of forging temperature from 1775 to 2175 F they found that the lower temperature gave a better carbide distribution. When the carbides occur intergranularly the rupture life is shortened. As the temperature of processing increased the rupture life improved at some sacrifice to tensile strength. Figure 8 illustrates the effect of forging temperature on stress rupture and tensile properties. Similar studies on the effects of forging practice on properties of other alloys would be worthwhile.

Chilling by cold dies impairs the forgeability and ductility and increases the strength of nickel-base alloys. In some superalloys, precipitation reactions may occur in the regions cooled to sufficiently low temperatures. For these reasons, it is desirable to use heated dies in forging superalloys. A typical die temperature in press forging is 1000 F. Die temperatures for hammer forging normally do not exceed 600 F.

Until die materials that will operate near the normal temperatures for hot-working nickel-base superalloys are developed, most forging companies use an insulation material between the die and workpiece. Sheet metal, asbestos, and glass have been used successfully for that purpose.

Nickel-base superalloys require as much as twice the forging pressure needed for steels. These alloys are sensitive to forging rate, forging reduction, and "cold work" at normal forging temperatures. Therefore, strict control of the forging process is a prerequisite to achieving a sound, high-quality forging.

Nickel-base alloys are damaged by contamination with sulfur. Some furnaces contain sulfur-rich scale from previous heating cycles, or use reducing atmospheres with enough sulfur to be harmful. The recommended practice is to support the billet or preform on clean brick or a plate of a heat-resistant alloy, and use natural gases or low-sulfur oils as furnace fuels. Slightly oxidizing conditions are recommended to reduce sulfur pickup from furnace atmospheres.

Poor thermal conductivity can have two effects on the forging. First, because nickel-base-alloy thermal conductivity is lower than that of steels, longer soaking periods are required to insure complete solution of precipitated phases and compounds. Where there

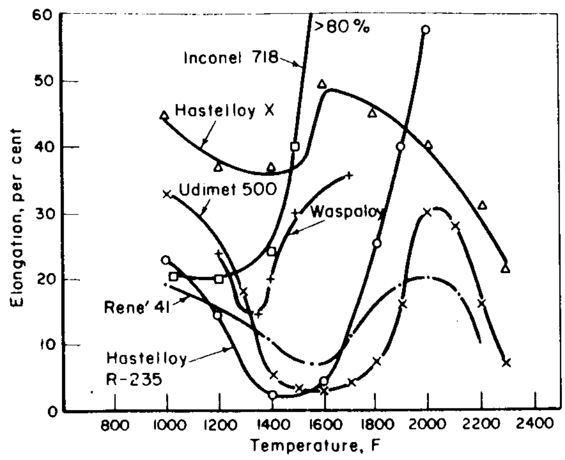


FIGURE 7. ELONGATION VALUES IN SHORT-TIME ELEVATED-TEMPERATURE TENSILE TESTS FOR SEVERAL NICKEL-BASE SUPERALLOYS (REF. 21)

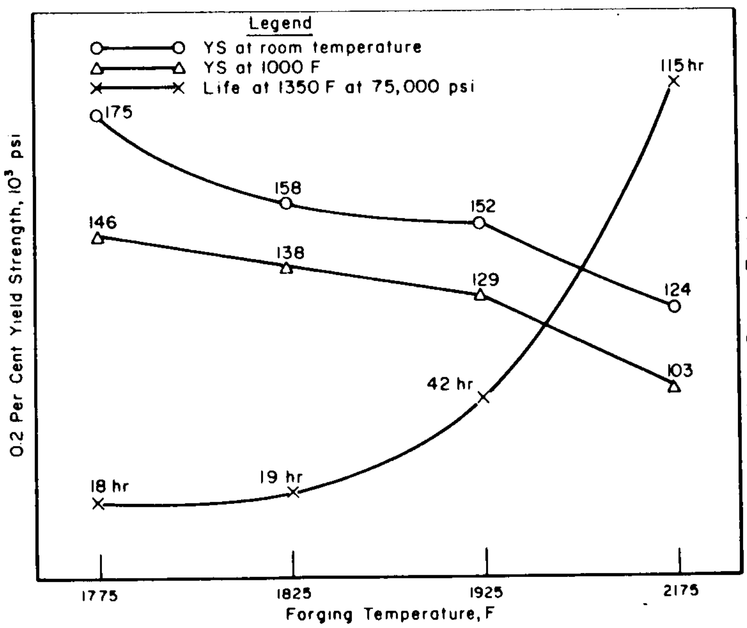


FIGURE 8. EFFECT OF FORGING TEMPERATURE ON TENSILE AND STRESS-RUPTURE PROPERTIES (REF. 22)

All tests were performed on fully heat-treated material.

is a chance of preferential heating due to billet orientation in the furnace, a safe practice is to turn the billet frequently and maintain minimum contact with the support material.

The second effect associated with low thermal conductivity is the change in volume that occurs during precipitation and the dissolving of the precipitate. Often internal cracks can occur and not be obvious until nondestructive testing detects the flaw in the final part. To insure a forging free of internal cracks the preform or billet should be preheated into the precipitation range and held to equalize the temperature then heated to the forging temperature, or heated slowly about 50 F per hour through the temperature range where precipitation occurs.

As for other difficult materials, the initial forging operations on nickel-base superalloys should include light reductions and frequent reheating. The typical coarse, as-cast grain structure must be destroyed by small, uniform deformations at high forging temperatures to develop a tougher structure. Reductions of about 10 per cent are sufficient if the operation is completed above the recrystallization temperature. Reductions below the recrystallization temperature must be avoided in order to prevent abnormal growth in subsequent heat-treating operations. After the early breakdown reductions, or in forging wrought billets, reductions should range from 15 to 30 per cent. Reductions of that order are necessary to insure a fine-recrystallized-grain size after solution-heat treatments.

The final forging temperature is important to the quality of the forging. Low temperatures are recommended; however, care must be exercised to avoid cold working or workling below the solution-treatment temperature. The forging would be highly strained and therefore develop coarse grains on subsequent heat treatment, damaging the mechanical properties. Furthermore, to exceed the elastic properties, the final forging operation should impart a reduction of at least 10 per cent.

During forging of nickel-base alloys, a lubricant is necessary between the part and die to reduce their natural tendency to seize and gall. Typically with steels, the natural oxide formed upon heating serves as a parting agent; however, with the oxidation-resistant nickel-base alloys, a parting agent must be introduced mechanically. Lubricants and parting agents containing sulfur are undesirable. The most commonly used lubricants are mixtures of graphite and oil. Other materials that have been used with varying degrees of success are glass, mica, sawdust, and asbestos. Those materials help to minimize the chilling effect of cold dies.

Figures 9 and 10 show some nickel-base alloy forging after subsequent machining operations.

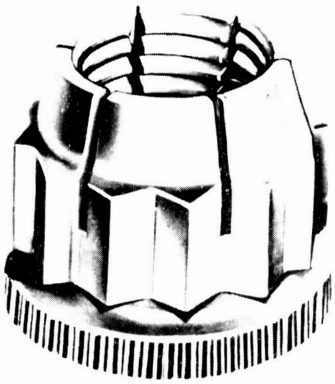


FIGURE 9. ELASTIC NUT FORGED AND MACHINED FROM ALLOY X-750

Courtesy of The International Nickel Company.

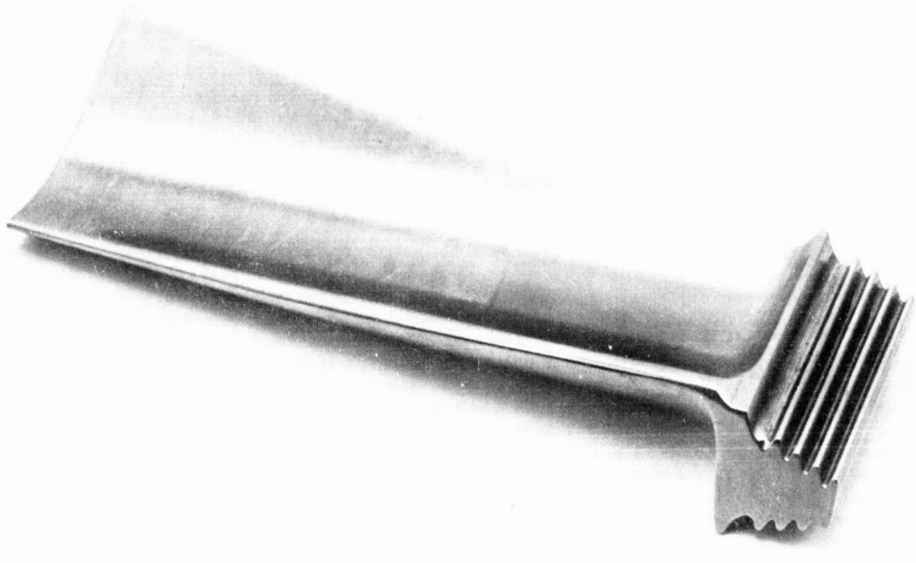


FIGURE 10. TURBINE BLADE FORGED AND MACHINED FROM INCONEL 700

Courtesy of The International Nickel Company.

Cobalt-Base Alloys. Cobalt-base superalloys are classed in two categories on the basis of their hardening mechanisms (Ref. 20). The first class of alloys is hardened by the combination of solid-solution and carbide precipitation. Its forgeability is equal to that of the iron-base superalloys over a temperature range of 1600 to 2300 F. As a result of the higher carbon content required in cobalt alloys to form the hard metallic carbides, the forging pressures are on the order of 3 to 4 times greater than for the iron-base alloys. Alloys that fall in this class are V-36, HS-25, S-816, and L-605.

The second class of alloys is hardened by precipitation reactions that limit the forging temperature range to between 1800 and 2200 F. This limit is established by the onset of precipitation and the formation of low-melting constituents. Fairly good forgeability is exhibited by alloys in this class like J-1570 and J-1650. Forging pressures are similar to those of the cobalt alloys hardened by solid solution.

Cobalt-base alloys are affected greatly by changes in forging temperatures and reductions. If these conditions are not controlled, coarse grains result and many of the mechanical properties, such as the ductility, notch toughness, and fatigue strength, are impaired.

Above 2150 F most cobalt-base alloys experience grain growth. Extended times at these elevated temperatures should be avoided.

In working with cobalt-base alloys, attention must be given to the typically low thermal conductivity. Stepwise heating can be used to shorten the soaking time required at the forging temperature. Heating schedules should include a soaking period of 1 hour per inch of the maximum cross section to insure temperature uniformity. Without long soaking periods there is a danger of variable properties due to variable grain size.

The cobalt superalloys most widely used as forgings are S-816 and L-605. At the highest practical forging temperature, these alloys exhibit work hardening. This means that as the reduction increases, the pressure required to produce deformation increases. Therefore, based on equipment capability and alloy forgeability, the total reductions are small. A typical reduction range is 20 to 30 per cent (Ref. 21). Higher reductions sometimes cause the temperature to increase into the range where incipient melting occurs. On the other hand, lower reductions of about 5 per cent do not impart sufficient strain to cause uniform recrystallization, and exaggerated grain growth results. To restore the ductility sufficiently to allow further reduction, reheating cycles are employed. During the reheating cycle, recrystallization takes place within the part and the ductility increases accordingly.

Surface cracks sometimes appear on a forged part, generally as a result of thermal gradients or a concentration of a hard precipitate that is resistant to deformation. These cracks must be removed between forging cycles by some mechanical means such as grinding.

To achieve a total reduction on cobalt-base alloys equivalent to that used on steels, at least four forging steps with intermediate reheat cycles are required. Typical operations and forging temperatures for several alloys are:

Typical Operation	Recommended Forging Temperature, F: S-816	L-605 (AA-25)	J-1570
Disk Forging			
Upset 1	2150	2150	2100
Upset 2	2250	2250	2200
Block	2200	2200	2150
Finish	2200	2200	2150
Disk With Integral Shaft			
Draw one end	2150	2150	2100
Roll shaft	2250	2250	2150
Block	2150	2150	2100
Finish	2150	2150	2100

ROD, WIRE, AND TUBE DRAWING

Drawing is a cold-working process in which the cross section of a long workpiece is reduced by pulling it through a die. Semifinished shapes are cold drawn into rod, wire, and tubular products for a variety of applications. Drawing is capable of producing better finishes, closer tolerances, and thinner sections than hot-working processes. Monel, Inconel, and Hastelloy C tubing is used for the manufacture of bourdon and thermocouple protection tubing and in cryogenic applications. Other superalloys such as Hastelloy C and X, Inco 702, Haynes 25, and Waspaloy find high-temperature tube requirements in steam-power and chemical-process plants. Rod and wire products find application as welding wire, elements in vacuum tubes, wire cloth, and corrosion-resistant fasteners.

Rod and Wire. Large-diameter rod is cold drawn in straight lengths on a standard drawbench. Individual bull blocks are used for drawing 1/2 to 1-inch-diameter rod. A block is a drum, ordinarily driven by an individual motor, that pulls the rod or wire through the die and produces a coil.

Wire rod approximately 0.3 inch in diameter is annealed and pickled prior to the start of cold drawing. Total reductions of as much as 40 per cent can be taken before intermediate annealing is required. For annealing, the wire is passed through a bright annealing furnace where an atmosphere of ammonia and cracked hydrogen prevent any scaling.

In the early stages of drawing, the wire is pulled through the die by revolving bull blocks. Finer wire, down to 0.001-inch diameter, is produced on high-speed multidie drawing machines that draw the wire continuously through diamond dies submerged in oil.

A variety of lubricants are used during the initial stages of drawing; lead and copper coatings are frequently used. Copper coatings in combination with chlorinated paraffin are used in cold-heading operations (Ref. 8).

Air Force studies (Ref. 23) have shown that ultrafine-diameter (0.0006 inch) superalloy wire can be produced, but fabrication procedures and production history becomes very important as drawing progresses. Drawability problems and excessive die wear occur from contaminated wire surfaces caused by improper annealing or failure to completely remove lubricants from the wire before annealing. Vacuum-melted materials are easier to process than air-melted ingots. Workability was better because of fewer inclusions and less gasiness.

Cold-drawn rod is available in certain nickel-base alloys in sizes from 1/2 to 3-1/2 inches in diameter and up to 34 feet in length. As indicated above, fine-diameter wire is available in these alloys in large-coil form. Larger diameter Hastelloy wire, for example (1/32 to 1/4 inch in diameter) is available in length multiples of 20 feet (Ref. 9).

Tubing. Monel, Inconel, and Incoloy tubing are produced by cold drawing extruded tube shells. Most other superalloys are fabricated into tubing by seam welding roll-formed sheet and drawing it to the size desired. Extruded tube shells have not been successfully produced for these alloys.

Drawbenches that take a single draft are used for tube drawing. Hydraulic and mechanical benches operate at speeds ranging from 10 to about 150 feet per minute. They can produce lengths up to 100 feet, which are later cut to the dimensions ordered. A bench used for drawing seamless tubes is shown schematically in Figure 11.

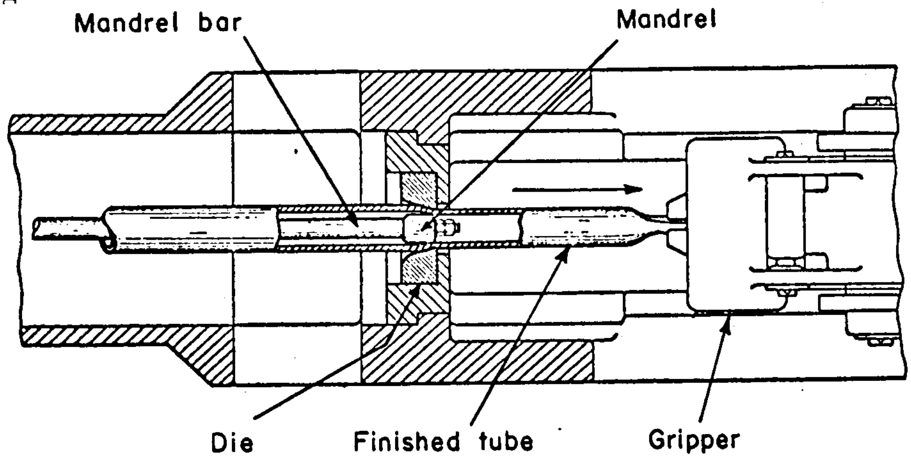


FIGURE 11. DIAGRAMMATIC VIEW OF DRAWBENCH SHOWING SEAMLESS TUBE IN THE PROCESS OF DRAWING (REF. 17)

Monel and Inconel seamless tubing are available from Inco in sizes 1/2 to 5-inch OD x 0.035 to 0.259-inch wall thickness and lengths up to 85 feet. Size limits on seamless and "Weldrawn" tubing from Superior Tube Company are listed below (Ref. 24).

Alloys	Tube Dimensions, inches: Outside Diameter	Wall Thickness: Maximum	Wall Thickness: Minimum
Monel, Inconel, Incoloy	1.125	0.035	0.008
	0.012	0.004	0.0015
Waspaloy, Haynes 25, Hastelloy C and X	1.125	0.035	0.008
	0.012	0.004	0.002

SECONDARY DEFORMATION PROCESSES

The primary wrought products can be converted to more useful shapes by secondary deformation processes. All of the conventional techniques used for that purpose have been applied successfully to nickel-base alloys. Most of them have also been used for cobalt-base alloys. Descriptions of many of the common forming processes and the limits imposed by the characteristics of the materials of interest are covered in this section of the report.

The severity of deformation required to produce a part depends on the relative shapes and dimensions of the blank or preform and the completed object. The properties of the workpiece material determine whether the desired change in shape can be accomplished successfully. Failures in forming are caused by rupture, buckling, or a combination of these. Rupture results from lack of ductility under imposed tensile stresses; excessive compressive loading causes elastic or plastic buckling. Methods for predicting the formability of sheet materials from their mechanical properties in simple tests were developed during an extensive study for the U. S. Air Force by Ling-Temco-Vought, Incorporated (Refs. 25,26). These investigations indicate that failures in conventional forming operations result from the mechanisms indicated in Table VIII (Ref. 27). The table also indicates the mechanical properties found to correlate with limiting deformations in different types of forming operations. Higher values of the parameters indicate better formability. The mechanical properties needed to calculate the formability parameters for a particular material can be determined from tensile and compressive tests conducted at the desired forming temperature. Other organizations are also investigating the correlations between standard mechanical properties and the performance of materials in specific forming operations. As information of this kind is collected and systematized, it will become easier to predict the response of metals to deformation processing.

The forming limits set by necking or splitting correlate with ductility measurements in tensile tests. Deformation limits set by buckling failures correlate with the ratios of elastic modulus to the yield strength of the metal. Since changes in deformation temperature affect all of these mechanical properties, formability varies with temperature. Unfortunately, the information needed for predicting the effects of higher temperatures on formability are not ordinarily available for many materials of interest.

TABLE VIII. TYPES OF FAILURES IN SHEET-FORMING PROCESSES AND MATERIAL PARAMETERS CONTROLLING DEFORMATION LIMITS (REF. 25)

The parameters can be determined in tensile and compressive tests.

Process	Cause of Failure: Splitting	Cause of Failure: Buckling	Ductility Parameter[a]	Buckling Parameters[b]
Brake forming	x		ϵ in 0.25 in.[c]	
Dimpling	x		ϵ in 2.0 in.[d]	
Beading				
Drop hammer	x		ϵ in 0.5 in.[c]	
Rubber press	x		(ϵ in 2.0 in.)(S_u)	
Sheet stretching	x		ϵ in 2.0 in.	
Joggling	x	x	ϵ in 0.02 in.	E_c/S_{cy}
Liner stretching	x	x	ϵ in 2.0 in.[e]	E_t/S_{ty}
Trapped rubber, stretching	x	x	ϵ in 2.0 in.[f]	E_t/S_{ty}
Trapped rubber, shrinking		x		E_c/S_{cy} and $1/S_{cy}$
Roll forming		x		E_t/S_{ty}[g] and E_c/S_{cy}[h]
Spinning		x		E_c/S_{cy} and E_t/S_u
Deep drawing		x		E_c/S_{cy} and S_{ty}/S_{cy}

(a) ϵ indicates natural or logarithmic strain; the dimensions indicate the distance over which it should be measured.

(b) E_c = modulus in compression; E_t = modulus in tension; S_{cy} = compressive yield strength; S_{ty} = tensile yield strength; S_u = ultimate tensile strength.

(c) Corrected for lateral contraction.

(d) For a standard 40-degree dimple.

(e) The correlation varies with sheet thickness.

(f) The correlation is independent of sheet thickness.

(g) For roll forming heel-in sections.

(h) For roll forming heel-out sections.

Nickel- and cobalt-base alloys are almost invariably formed at room temperature. Whether or not advantages would result from forming at elevated temperatures depends on the specific material and forming operation. Experiments at Ling-Temco-Vought indicated that the ductility forming parameters for René 41 and L-605 alloys are better at room temperature than at elevated temperatures (Refs. 25,26). The effects of higher temperatures on the buckling parameters were variable but generally favorable. The optimum deformation temperatures for the buckling parameter were approximately:

Parameter[(a)]	Temperature, F René 41	Temperature, F L-605
E_t/S_{cy}	80	1000
E_t/S_{ty}	1000	80
E_c/S_{cy}	400	800
$(E_c/S_{cy})(S_{ty}/S_{cy})$	400	1100
E_c/S_u	>1500	>1000

(a) Parameters defined in footnotes to Table VIII.

The mechanical-property data available are usually too meager to predict the effect of forming temperatures on other alloys. The strengths and elongation values of most nickel-base and cobalt-base alloys change by less than 1/6 in the temperature range from 80 to 1000 F (Ref. 28). Raising the temperature in the range from 80 to 1000 F apparently improves the elongation values of René 41 and V-36 but lowers the values for Hastelloy X, S-590, HS-21, and S-816 alloys (Ref. 28). Even such scanty information provides some guidance about the effects to be expected if forming temperatures are changed.

BLANK PREPARATION

Introduction. The preparation of a blank for metal forming may be as simple an operation as cutting a tube to the length desired or as complicated as cutting a shape that closely resembles the shape of the final sheet-metal part. The size of the blank depends on whether the parts are formed to final dimensions or are to be trimmed after forming. The former is preferred where possible to minimize scrap loss. Since the practices suitable for preparing blanks for different types of metal-forming operations bear many similarities, they are summarized in this section. Some of the special precautions necessary with nickel-base and cobalt-base alloys in processing are emphasized.

Since there is a wide variation of strength and hardness between the various nickel- and cobalt-base alloys, it is difficult to generalize the techniques of blank preparation. Most of the materials are prepared for forming in the annealed or solution-treated condition; conventional blank preparation methods may, therefore, be used. The major precaution to be taken in handling these alloys is to prevent contamination by sulfur if the material is to be heated or used at an elevated temperature. Sulfur severely embrittles nickel, and has similar but less marked effects on cobalt-base alloys.

Blank Layout. When more than one part is to be obtained from a sheet of material, the positioning of the blanks on the sheet can determine the scrap loss. The amount of blanking scrap generally is determined by the dimensions of the sheet, the shape of the formed part, and the ingenuity of the layout man. The choice of sheet dimensions can be important. The normal procedure is to first determine the method of blank preparation and the clearance required around the blank. A pattern is then made that includes the edge allowance. Several arrangements of the pattern on a sheet are then tried and the one that requires the least material is selected. The selection of the sheet size may depend on ease of handling, scrap loss, or blank-preparation method. Where a large or complex shape blank is required, it may be feasible and economical to weld smaller blanks together to obtain the shape desired. This procedure can be carried one step further by producing a preformed blank to reduce the amount of forming required.

Shearing. Shearing is generally the most economical method of blank preparation and is widely used. Conventional shearing equipment suitable for stainless steel can be used with most nickel- and cobalt-base alloys in either the annealed or solution-treated condition. There is a tendency for the material to drag over the blade and form a burr so that clearances of 5 per cent of the material thickness should be maintained to minimize this effect (Ref. 29). Because of the shearing forces required, shearing the materials in the heat-treated condition is not recommended for the high-strength materials.

When thicknesses above 0.125 inch are sheared, some difficulty may be expected from edge roughness. This can be minimized by using thick shear blades to minimize deflection. Heavy hold-down pressures will also help maintain a smooth cut. Edge cracking is generally not a problem with the nickel- or cobalt-base alloys during shearing. However, some of the high-strength alloys in the heat-treated condition may be expected to show some cracking, especially in the sheet above 0.250 inch. The cutters should be sharp and free of nicks to assure a smooth edge. Blades made from W-2 steel are considered satisfactory.

Shearing of sheet or plate of high-nickel alloys in the annealed condition generally requires slightly greater power than is needed for shearing soft steel of equal thickness. Table IX shows the comparative shear loads for Monel 400, Nickel 200, and Inconel 600 sheet in three rolled conditions. Naturally the harder the material the higher the shearing force required. The results were obtained from shearing material of three thicknesses between 0.062 and 0.125 inch.

TABLE IX. COMPARATIVE SHEAR LOAD REQUIRED TO SHEAR MONEL 400, NICKEL 200, AND INCONEL 600 SHEET AND STRIP (REF. 30)

Material	Temper	Shear Load in Per Cent of Same Thickness in Mild Steel	Sheet Tensile Strength, psi	Hardness, Rockwell B
Monel 400	Soft	116	81,150	67
	Half hard	128	87,500	86
	Full hard	130	136,450	104
Nickel 200	Soft	113	68,500	43
	Half hard	119	75,200	78
	Full hard	127	113,000	100
Inconel 600	Soft	119	91,700	74
	Half hard	127	115,000	99
	Full hard	131	145,000	109

Blanking. Blanking is normally performed on a punch press to produce a blank with the desired shape in one operation. Concentric shapes in nickel- and cobalt-base alloys have been produced by this method in thicknesses up to 0.125 inch. Standard blanking dies or steel-rule dies may be used. The die clearance should be 0.005 inch or less for best results.

Dies for blanking nickel- or cobalt-base alloys should be rigid, and guide pins should be used to insure proper alignment. This requirement becomes more important for thicker sheet. Insufficient stiffness in the tooling causes die failure and ragged edges on the blanks. The cutting edge of the tools must be sharp and free of irregularities.

Minimum hole sizes for punching annealed or quarter hard temper Monel 400, Nickel 200, and Inconel 600 alloy sheet are given in Table X. The ratio between material thickness and hole diameter decreases as the thickness of material increases.

TABLE X. RELATION BETWEEN SHEET THICKNESS AND MINIMUM PERMISSIBLE HOLE DIAMETER FOR PUNCHING MONEL 400, NICKEL 200, AND INCONEL 600 ALLOY (REF. 30)

Sheet Thickness, T, inch	Approximate Minimum Diameter of Hole
0.018 to 0.034 inclusive	1.5 T
0.037 to 0.070 inclusive	1.3 T
0.078 to 0.140 inclusive	1.2 T
0.141 and thicker	1.0 T

The die and punch clearance for punching thin-sheet Monel 400, Nickel 200, and Inconel 600 should be about the same as for net steel punching. When the thickness exceeds 1/8 inch, it may be desirable to use slightly less clearance than is recommended for steel. This will reduce the tendency to burr and will produce a clean hole. A die clearance of 5 to 10 per cent of the material thickness should be considered for heavier stock. The clearance between the punch and the stripper plate should be very close, within 0.005 inch to prevent difficulties in removing the punch from the material.

Several grades of tool steel have been used for punching Monel 400, Nickel 200, and Inconel 600 with success. They include die steels with 1.5 per cent carbon and 13 per cent chromium, and the 18 per cent tungsten, 4 per cent chromium, 1 per cent vanadium high-speed steel. Both the punch and the dies should be heat treated to Rockwell C 58-61 for best tool life.

The use of a lubricant during punching will increase tool life. Sulfurized fatty mineral oil has been found suitable although care must be exercised in assuring that all residue has been removed from the material before it receives any thermal treatment.

The lineal velocity for blanking Monel 400, Nickel 200, and Inconel 600 should be between 30 and 45 feet per minute. Higher speeds will result in decreased tool life.

Band Sawing. Band sawing is used for cutting nickel- or cobalt-base alloys in thicknesses above 0.250 inch. Sawing eliminates edge taper but has the disadvantage of creating a burr that must be removed from the blank.

The saws used on nickel- or cobalt-base alloys should be of rigid construction and have ample horsepower to maintain a constant speed during cutting. The equipment should provide automatic positive feeding, band tensioning, and a positive flow of the coolant. A non-sulfurized coolant is preferable if the material is to receive any thermal treatment. Blades with pitch and widths recommended by the manufacturer should be used for best results. Germann and Shaver (Ref. 29) found that 0.093-inch Inconel X-750 could be economically sawed with a high-speed steel blade with a precision-set, raker-type tooth and a 32 pitch. A pressure-resistant oil was brushed on the cutter teeth to prevent chip welding and a flood of soluble oil was applied to cool the tool. A blade speed of 60 surface feet per minute and a light feed pressure (approximately 1/2 inch per minute) resulted in no appreciable wear to the blade. Ferguson (Ref. 31) reported that band sawing of thick Inconel X-750 resulted in rapid blade wear and low cutting rates.

Sawing tests on René 41, HS-25, and Hastelloy X in thicknesses of 0.010, 0.020, 0.040, and 0.060 inch were conducted with a low-carbon steel, hard-edged blade, 1/4 and 3/8 inch wide with a pitch of 32 teeth per inch (Ref. 32). With a blade speed from 50 to 60 surface feet per minute and manual feeding on 0.040 and 0.060-inch material, the blade life obtained expressed in lineal inches of material cut was 100 to 125 inches for René 41, 14 to 20 inches for HS-25, and 36 to 48 inches for Hastelloy X. The best blade life obtained in sawing 1-3/4-inch-thick René 41 bar was 60 lineal inches using a high-speed steel blade having a width of 1/2 to 1 inch, a pitch of 10 teeth per inch, standard set, and a speed of 25 to 50 surface feet per minute.

Slitting and Hand Shearing. Slitting and hand shearing is used to prepare long, narrow, thin blanks or to cut circles. Where contour changes are not too sharp, hand shearing may also be used for irregularly shaped blanks. The hand process is generally limited to 0.040-inch material in the annealed condition. Inconel X-750 with a hardness of Rockwell B 78-95 was cut without difficulty using a hand shears or snippers. It was found that the hand shears should be provided with blades that are "hard surface treated" for superior work (Ref. 29).

Conventional slitting equipment suitable for stainless steel and the drawbench type of equipment may be used successfully on nickel- and cobalt-base alloys. For best results, the equipment should be of rigid construction and the tooling maintained in a sharp condition.

Routing. Routing is a process that uses a milling cutter that is moved by hand to cut a stack of sheets to the desired contour. The router follows a template with the desired pattern. Although routing has been used successfully for preparing blanks from aluminum, the force required to hand feed a router in cutting nickel- or cobalt-base alloys makes the process limited in application. The development of automatic feed systems for routing could result in considerable time saving in the preparation of irregularly shaped nickel- and cobalt-base blanks. As with milling, high-speed steel cutters or carbide cutters should be used. In cutting Inconel X-750, steel cutters should be run at 15 to 20 surface feet per minute, while the carbide cutters could be run at 60 to 75 surface feet per minute (Ref. 29). A pressure-resistant oil was applied to the cutters as a mist while an abundant supply of coolant was supplied to the workpiece and cutter for best results.

Nibbling. Nibbling is a slow process usually restricted to the preparation of a small number of blanks. It can be used to produce irregularly shaped blanks, but the edges generally require smoothing if the blank is not trimmed after forming. Short tool life and high maintenance costs are normally associated with this type of blank preparation. It also has the same limitations as shearing regarding thickness of material that can be cut.

Thermal Cutting. For cutting nickel- and cobalt-base alloys, thicker than 0.250 inch, a thermal-cutting process may be used. The acetylene torch is unsatisfactory, but a carbon arc or iron-powder flame-cutting process may be used. Thick Inconel X-750 has been cut with the latter process with satisfactory results (Ref. 31). As might be expected, the flame-cutting process causes some grain growth near the face of the cut. Most of the heat-affected area should be removed by grinding after cutting.

Edge Conditioning. Nickel-base and cobalt-base alloys are deburred only to minimize damage to the forming tools or safety in handling. Most of the nickel- and cobalt-base alloys are not notch sensitive so that scratches in the edge of the blanks have little effect on formability. This was demonstrated by Germann (Ref. 29), who formed purposely scratched Inconel X-750 sheet with no deleterious effects.

Sharp edges, however, should be removed from the blank to prevent damage to the forming tools. The edges of blanked holes and cutouts as well as pilot holes should be deburred on both sides for maximum tool life.

Deburring and polishing can be done by draw filing or belt grinding on blanks up to 0.040 inch thick. For thicker materials, a grinding wheel or machining operation such as milling may be considered.

Surface Preparation. Surface imperfections such as scratches have very little effect on the formability of nickel- and cobalt-base alloys. A surface layer contaminated by sulfur can make the part structurally unacceptable especially if the part is to be used at elevated temperatures.

It is a good practice to remove oil, grease, and other soluble materials from the surfaces of blanks before heating them. Bend tests by Germann (Ref. 29), however, indicated that the presence of Tempilaq* or Tempilstik* markings on the surface of Inconel X-750 during heat treatment was not deleterious. The specimens were cleaned by vapor blasting after heat treating and before bend testing. He also found that identification marking of Inconel X-750 with Lectroetch 2611A** and an alternating current for 30 to 45 seconds did not introduce stress or deformation to the material. Subsequent heat treatment and vapor blasting obliterated the identification marks (Ref. 29).

Most of the nickel- and cobalt-base alloys are susceptible to attack when heated in the presence of certain contaminating materials. Sulfur, which may be present as a residue from many machining and forming lubricants, can cause trouble. Materials such as lead, zinc, aluminum, and magnesium used in forming tools, dies, or assembly positioning fixtures may also cause severe contamination. Such materials should be removed prior to any thermal treatment by vapor degreasing, alkaline cleaning, and passivating. After cleaning, the parts should be wrapped in paper if they are not to be thermally treated immediately.

The removal of scale or oxide coatings developed during annealing and stress-relief operations can be accomplished on Inconel X-750 by using a stainless steel descaling bath (Ref. 29). This bath consists of 3 to 5 per cent hydrofluoric and 15 to 20 per cent nitric acid; it is

*Produced by Tempil Corporation, New York, New York.
**Produced by The Lectroetch Co., East Cleveland, Ohio.

used at 120 to 140 F. The parts should be treated for a maximum time of 30 minutes. Often the scale formed during heat treatment is very tenacious. By using a pretreatment coating of Turco 4367*, the scale tenacity can be reduced and the material can be chemically descaled with a 20 per cent nitric acid solution at 70 to 100 F in 15 minutes (Ref. 29).

The same solution has been used for etching René 41, HS-25, and Hastelloy X (Ref. 32), and M-252. Weight-loss determinations after descaling revealed the etch rate to be less than 0.0001 inch per minute. No surface damage was disclosed by metallographic examination up to 500X magnification. A pickling solution of 35 per cent hydrofluoric and 5 per cent nitric acid was found to be more efficient at room temperature than the other solution at 130 F but resulted in greater weight loss of material.

Turco Pretreat* was found to be effective in reducing scale formation on René 41, HS-25, and Hastelloy X, provided the thermal treatment did not exceed 2200 F. It has questionable value when used on HS-25, since HS-25 is annealed at 2250 F. Scale conditioning was found to be beneficial on all three alloys. The alkaline permanganate reacts with the scale to form more readily soluble oxides. It may also cause some dissolution of the ceramic Pretreat coating, which will expose the scale to attack by the acid pickle. Scale conditioning with Turco 4338* or an equivalent alkaline permanganate solution for the following times was found to be helpful: René 41, 30 to 60 minutes; HS-25, 90 to 120 minutes; and Hastelloy X, 60 to 90 minutes.

BRAKE BENDING

Introduction. Brake forming is a simple, versatile forming operation widely used for forming flat sheets into sections such as angles, channels, and hats. The process uses inexpensive, simple tooling that can be quickly adapted to different part shapes. Brake forming is used mostly for making parts to wide tolerances and for preforming operations on close-tolerance parts. Handworking or sizing operations are usually required to produce parts with closer dimensional tolerances.

The springback allowance for annealed nickel- and cobalt-base alloys is normally less than 10 degrees. When the aged alloys are bent, the springback may be as high as about 30 degrees. If the bend radii are sufficiently large, no unusual problems are encountered.

*Produced by Turco Products Co., Wilmington, California.

Principles of Bending. In bending, the metal on the inside of the bend is compressed, or shrunk, while that on the outside of the bend is stretched. This is shown in Figure 12 for two typical brake-forming setups. In air bending, the workpiece is supported only at its outer edges so that the length of the ram stroke determines the bend angle, α, of the part. The radius of the punch controls the inside radius of the workpiece. In die bending, the sheet is forced into a female-die cavity of the required part angle, α.

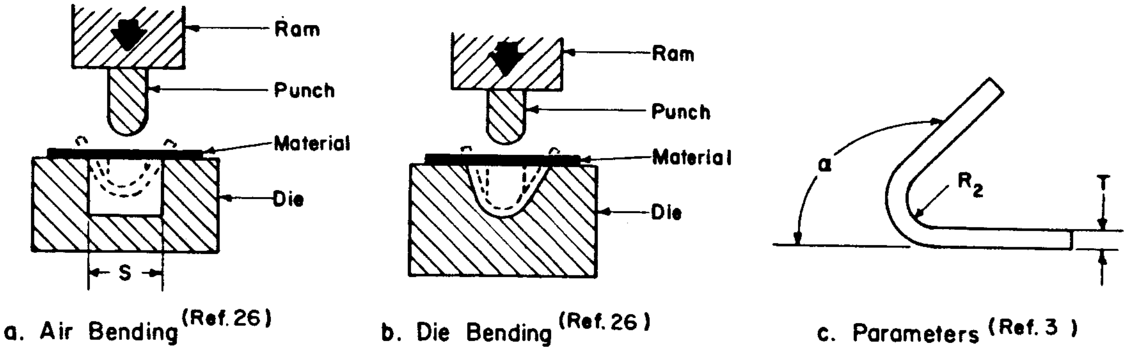


FIGURE 12. TYPICAL BRAKE-FORMING SETUPS AND PARAMETERS

The limiting span width, S, in Figure 12a depends on the sheet thickness, T, and the punch radius, R. According to Wood, et al. (Ref. 33), the practical limits for brake bending lie between:

$$S = 3R + 2T \text{ and } S = 2.1R + 2T \quad . \tag{1}$$

Those variables and the bend angle control success or failure in bending. Larger radii are needed for thicker sheet, and the ratio of R/T should also be increased for larger bend angles. The limiting bend angle and bend radius depend on the ability of the metal to stretch. If the operation is too severe, the metal cracks on the outer surface of the bend.

Presses Used for Brake Forming. A press brake is a single-action press with a very long and narrow bed. Its chief purpose is to form long, straight bends in pieces such as channels and corrugated sheets.

Brake presses are commercially available with capacities ranging from about 8 to 2000 tons. Figure 13 shows a typical brake press having a capacity of 60 tons. For the bending of relatively thin sheet metal, the press capacity can be relatively small and hand operated.

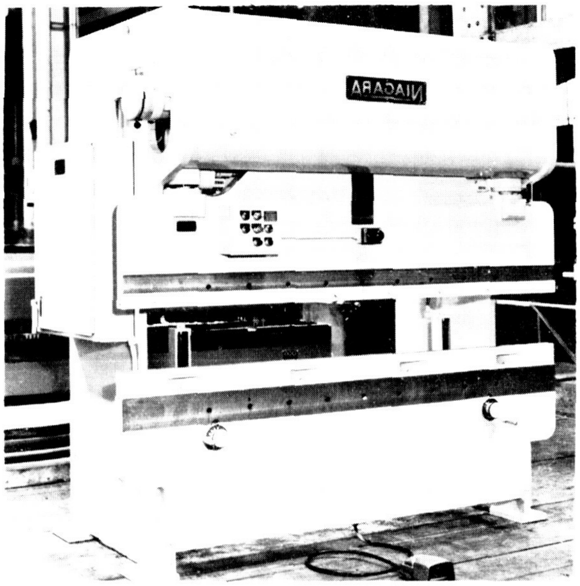


FIGURE 13. 60-TON MECHANICAL PRESS BRAKE

Courtesy of Niagara Machine and Tool Works, Buffalo, New York.

Table XI lists the capacities and other pertinent information on brake presses available from one manufacturer.

Tooling. The nickel-chromium and cobalt-chromium-nickel alloys have a tendency to gall with die materials; consequently, lubricants must be used with conventional forming operations. Dies and punches for press-brake forming at room temperature may be made from suitably heat-treated low-alloy steels, such as SAE-3140 and 4340. Tool steels, especially those high in chromium, and Meehanite cast irons are used for punches and dies that are to be used both at room and elevated temperatures up to about 1400 F. The use of hard chromium plating on the dies lessens the tendency to gall, as does the use of aluminum bronze or tungsten-carbide tooling.

Beryllium copper also is a desirable material for forming dies, according to Republic Aviation (Ref. 29). One alloy, Berylco 20 can be used at temperatures to 1100 F in air; a second alloy, Berylco 10, requires surface protection when heated above 700 F. Dies from both of these materials can be precisely cast to shape and for many applications require no further working. Thus, die costs are lower than with other methods and materials.

TABLE XI. CAPACITIES AND OTHER TYPICAL INFORMATION ON BRAKE PRESSES (REF. 34)

Model	Capacity, tons		Range of Bed Lengths, feet		Stroke		Bending Capacity, feet, Mild Steel With Standard Stroke for Thicknesses						Motor Horsepower	Range of Shipping Weight, pounds	
	Mid-Stroke	Near Bottom of Stroke	Longest	Shortest	Standard Length, in.	Speed, surface feet/minute	16 Gage	3/16 In.	1/4 In.	1/2 In.	3/4 In.	1 In.		Largest	Smallest
						Mechanical Press Brakes									
1B-15	--	15	10	4	2	20-50	4	3/4	--	--	--	--	3/4-1	3,800	2,500
1B-25	--	25	12	6	2	20-50	6-1/2	1-1/2	--	--	--	--	1-1/2	5,200	4,500
1B-36	36	55	12	6	2-1/2	40	12	3	--	--	--	--	3	8,300	6,900
1B-60	60	90	14	6	3	40	18	6	--	--	--	--	5	17,800	10,925
N-90	90	135	14	6	3	36 and 12	--	11	6	--	--	--	7-1/2	25,350	12,500
N-115	115	175	14	6	3	36 and 12	--	15	10	--	--	--	10	30,000	15,400
N-150	150	225	16	6	3	33 and 11	--	19	13	--	--	--	15	50,000	24,800
N-200	200	300	18	8	4	30 and 10	--	23	18	6	--	--	20	53,000	32,000
N-260	260	400	18-2/3	8-2/3	4	30 and 10	--	--	24	8	--	--	20	67,500	37,000
N-335	335	500	18-2/3	8-2/3	4	30 and 10	--	--	25	10	5	--	25	90,000	60,000
N-400	400	600	24	10	4	30 and 10	--	--	30	12	5	--	30	120,000	64,000
N-520	520	750	24	10	4	23 and 7	--	--	--	18	10	--	40	157,000	79,500
N-650	650	1000	24	10	5	23 and 7	--	--	--	24	12	6	40	180,000	92,000
N-825	825	1250	22	14	6	20 and 6	--	--	--	30	17	10	50	194,000	133,000
N-1000	1000	1500	24	14	6	20 and 6	--	--	--	--	21	12	50	230,000	141,000
						Hydraulic Press Brakes									
HD-200	--	200	18-2/3	8-2/3	12	21 and 34[a]	--	14	12	--	--	--	25	50,000	26,500
HD-300	--	300	18-2/3	8-2/3	12	25[a]	--	--	16	8	--	--	30	52,600	29,000
HD-400	--	400	18-2/3	8-2/3	12	26[a]	--	--	--	12	6	--	40	67,000	33,000
HD-500	--	500	18-2/3	8-2/3	12	25[a]	--	--	--	14	9	--	40	85,500	50,000
HD-600	--	600	24	10	12	25[a]	--	--	--	16	10	--	50	119,000	59,800
HD-750	--	750	24	14	12	21[a]	--	--	--	22	14	10	60	120,000	79,500
HD-1000	--	1000	24	14	18	21[a]	--	--	--	--	18	14	75	204,000	102,000

(a) Normal press speed gives rated capacity. High press speeds along with press tonnage ratings are as follows: HD-200, 57 and 65 in./min at 70 tons; HD-300, 44 and 62 in./min at 120 tons; HD-400, 51 and 62 in./min at 160 tons; HD-500, 54 and 58 in./min at 200 tons; HD-600, 56 and 51 in./min at 240 tons; HD-750, 48 and 47 in./min at 300 tons; and HD-1000, 58 and 44 in./min at 400 tons.

Punches of any of the alloys are made to the desired bend radii. The female die may be a "V" die or a channel die. For brake forming at room temperature, a hard-rubber insert sometimes is placed in the channel die to avoid scratching the formed parts. The surface of the punch must be free of defects, such as nicks, where it contacts the blank.

Zinc-alloy (Kirksite) punches and dies have been used for producing limited quantities of brake-formed parts from René 41, Hastelloy X, and HS-25 (Ref. 32). When more than about 50 parts are involved, steel dies are recommended for these alloys.

When steel tooling is used for hot forming, it is sometimes covered with a protective coating to prevent scaling and pitting. A satisfactory coating can be built up by spraying a thin layer of Ni-Cr-B alloy on the surface of the grit-blasted tool and fusing the deposit at 1875 F. The coating then can be polished to the desired surface smoothness.

Bending Procedures. Nickel- and cobalt-base blanks for bending on a press brake are prepared by methods described in the section on blank preparation. Normally these alloys are bent in the annealed (solution treated) condition at room temperature because many of the alloys are age hardenable and aging begins at about 1100 F. Usually there are few advantages of bending at 1000 to 1050 F over bending at room temperature.

Nickel- and cobalt-base alloys usually require lubrication to insure good die life and good surface finishes. For mild-forming operations, polar lubricants such as castor oil, lard oil, and sperm oil may be used. Severe deformations require the use of surface-active compounds such as sulfurized or sulfo-chlorinated mineral oils and paraffins and metallic soaps. These can be pigmented or diluted with neutral thinning oils as required. Lubricants containing white lead or molybdenum disulfide are not recommended for use with the nickel- and cobalt-base alloys because they are difficult to completely remove prior to annealing or high-temperature service. Both lead and sulfur are detrimental to these alloys at elevated temperatures. The sulfurized oils may be used only if the parts are thoroughly cleaned in a vapor degreaser or alkaline cleanser after forming.

Bending Limits. Failures in bending always occur by splitting in the outer fibers of the bend. A number of methods have been developed for predicting the minimum radius to which a material may be bent without fracture (Refs. 33,35). They are usually based on the assumptions that the material is bent in plane strain and that the strain at which a workpiece splits in bending is equal to that strain at fracture in a tensile specimen. The natural or logarithmic strain in the outer fiber of a bent structure is

$$\bar{E} = \ln \left(\sqrt{1 + T/R} \right) \quad , \qquad (2)$$

where

T = thickness

R = inner bend radius.

In tensile tests:

$$E = \ln \frac{100}{100\ A_R} \quad , \qquad (3)$$

where A_R = reduction in area expressed in per cent.

Datsko and Yang (Ref. 35) showed that the minimum bend radii for various materials could be predicted fairly accurately by the following relationships:

$$\frac{R_{min}}{T} = \frac{50}{A_R} - 1 \quad (\text{For } A_R < 20) \qquad (4)$$

$$\frac{R_{min}}{T} = \frac{(100 - A_R)^2}{200 - A_R^2} \quad (\text{For } A_R > 20) \quad . \qquad (5)$$

The differences between Equations (4) and (5) arose from taking into account a displacement of the neutral axis during bending. Datsko (Ref. 35) considered the displacement to be significant in materials exhibiting large reduction-in-area values. The equations may be used to estimate minimum safe bending radii from tensile-property data found in handbooks. It is safer, of course, to determine the values on materials of interest on flat specimens.

Wood and associates (Ref. 33) determined the limiting tensile strain by measuring the elongation in a 0.25-inch gage length and correcting it for width strain. This is equivalent to the strain based on reduction-in-area values for biaxial stress but is affected by specimen geometry. To use their approach, tension tests are made on specimens marked with a grid of 0.25-inch squares. Then the data are used for the equations given in Table XII to construct a formability diagram like that shown in Figure 14. Their analysis

TABLE XII. EQUATIONS FOR CONSTRUCTING SPLITTING-LIMIT DIAGRAMS FOR BRAKE FORMING (REF. 33)

Terms:

R = radius of punch or inside of bend

T = thickness of workpiece

e = base of natural logarithms, or 2.718

α = part angle

ϕ = part angle where curve reaches a maximum; further bending does not increase strain (see Figure 14)

θ = angle of interest ranging from 0 to 180 degrees

$\dot{E}$ = corrected value of maximum strain based on 0.25-inch gage length

Equations:

where $\alpha > \phi$ (6)

$$R/T = 1/(2.718)^{2\dot{E}} - 1$$

where $\alpha < \phi$

$$R/T = 0.5\ [R/T \text{ from Equation (6)}]\ [1 + \sin(\theta - 90 \text{ deg})] \tag{7}$$

$$\phi = \frac{11.4 - R/T \text{ from Equation (6)}}{0.0845} \tag{8}$$

$$\alpha = \theta \frac{\phi}{180 \text{ deg}} \tag{9}$$

$$R/T = 0.5 \left[2.718^{2\dot{E}} - 1\right]^{-1} \left[1 + \sin\left(\frac{15.21\,\alpha}{(11.4 - 2.718^{2\dot{E}} - 1)^{-1}} - 90 \text{ deg}\right)\right] \tag{10}$$

takes bend angle as well as critical bend radius into account. Figure 14 is based on a material with a corrected limiting plane-strain value of E = 0.4. The curve would move to the right for materials exhibiting better ductility in plane-strain tensile tests.

Figure 15 shows such curves for several nickel- and cobalt-base alloys.

The brake bending limits for three nickel-base and two cobalt-base alloys are also given in Table XIII for bending at room temperature and 1000 F (Ref. 25). Hastelloy X, Inconel X-750, and L-605 bend equally well parallel or perpendicular to the direction of rolling. René 41 and the J-1570 cobalt-base alloy were more difficult to bend transverse to the major rolling direction than parallel to it. The L-605 alloy was much more readily bent at 1000 F than at room temperature; less improvement was found for bending René 41 at 1000 F than at room temperature.

Inconel X-750 can more readily be bent at room temperature than the J-1570, L-605, René 41, or Hastelloy X alloys. Bending René 41 at 2000 F was much more readily done than bending at room temperature.

Other experimental data in the literature on minimum bend radii for selected nickel-base alloys are given in Table XIV. These data are based on tests performed at room temperature at Republic Aviation Corporation (Ref. 29), Marquardt Aircraft Company (Refs. 37-39), and McDonnell Aircraft Corporation (Refs. 40,41). Waspaloy, Hastelloy R-235, and the M-252 alloy in the annealed (solution treated) condition are most readily bent; these sheets showed no directional properties with regard to bendability. The most difficult alloy to bend of those given in Table XIV was René 41. The alloys are much more difficult to bend after aging; bend radii of about 3.5 T being required compared with radii of 0.5 to 1.0 T for the annealed sheets.

Generally the design bend radii should be higher than the experimentally determined minimum bend radii by a factor of 0.5 to 1.0 T. This allows for variations from sheet to sheet of the same alloy grade.

Springback. Inconel X-750 in the annealed condition shows springback of only 0.5 to 1.0 degree for a 105 or 180-degree bend at room temperature, as shown in Table XIV. After aging, the same alloy shows up to 9-degree springback when bent over a 3.0 to 3.5 radius.

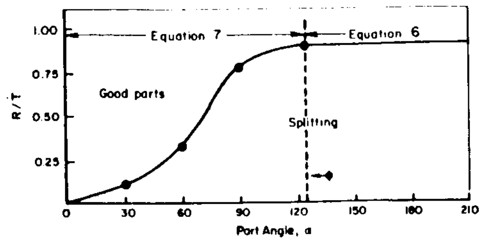


FIGURE 14. EXAMPLE OF A SPLITTING-LIMIT CURVE FOR BENDING (REF. 26)

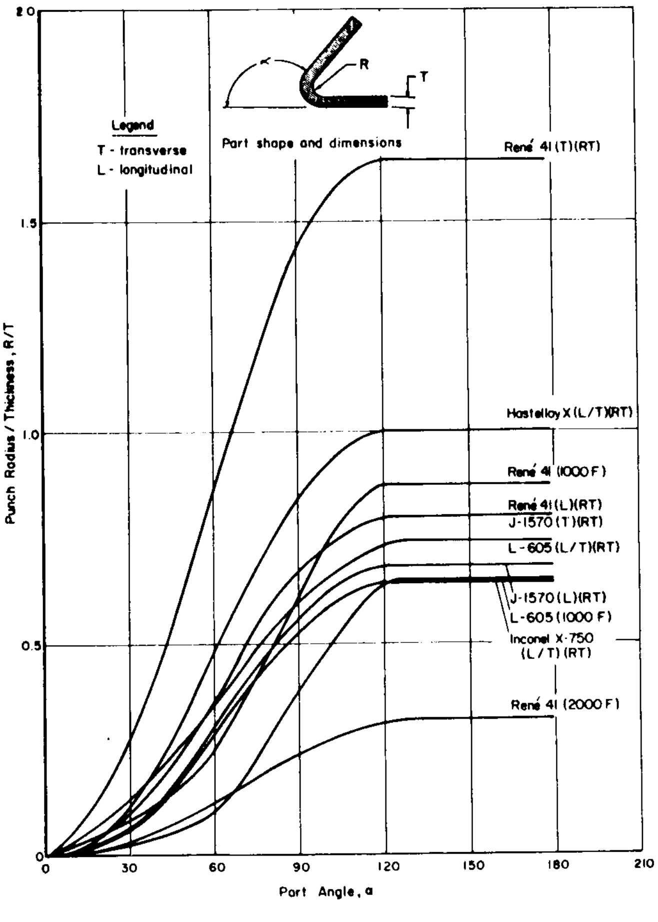


FIGURE 15. COMPOSITE BRAKE-BEND-LIMIT CURVES FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS (REFS. 26, 33)

TABLE XIII. BRAKE-BENDING LIMITS FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS (REF. 36)

Alloy	Grain Direction	Bending Temperature, F	Critical Bend Angle, α, degrees	Critical Bend Limits, R/T	Bending Limits, R/T, For Various Angles, α, Below Critical						
					30	45	60	75	90	105	120
Hastelloy X	L/T	RT	120	1.00	0.12	0.26	0.47	0.67	0.84	0.95	1.00
Inconel X-750	L/T	RT	124	0.64	0.06	0.14	0.28	0.41	0.52	0.60	0.63
René 41	L	RT	122	0.80	0.10	0.22	0.37	0.54	0.66	0.75	0.79
René 41	T	RT	113	1.64	0.28	0.53	0.84	0.16	1.44	1.58	1.64
René 41	L	1000	125	0.86	0.09	0.15	0.25	0.39	0.58	0.80	0.87
J-1570	L	RT	124	0.68	0.08	0.16	0.30	0.45	0.56	0.64	0.67
J-1570	T	RT	122	0.80	0.10	0.22	0.37	0.54	0.66	0.75	0.79
L-605	L/T	RT	120	1.00	0.12	0.26	0.47	0.67	0.84	0.95	1.00
L-605	L	1000	127	0.67	0.04	0.07	0.12	0.20	0.33	0.52	0.65

TABLE XIV. EXPERIMENTAL ROOM-TEMPERATURE BRAKE-BENDING LIMITS FOR SELECTED NICKEL-BASE ALLOYS

Alloy	Condition	Sheet Thickness, in.	Minimum Bend Radius, T	Bend Angle, degrees	Springback, degrees	Grain Direction to Bend	Hardness	Reference
Inconel X-750	Annealed	0.025	1.0	105 + 180	0.5-1.0	Transverse and longitudinal	--	29
	"	0.040	1.0	105 + 180	0.0-0.5	Ditto	--	29
	"	0.060	1.0	105 + 180	0.5-1.0	"	--	29
	"	0.093	1.0	105 + 180	1.0	"	--	29
	Solution treated and aged (1300 F – 20 hr)	0.025	3.5	105	4.0	Transverse	--	29
	Ditto	0.025	3.5	105	3.0	Longitudinal	--	29
	"	0.040	3.0	105	6.0	"	--	29
	"	0.040	3.0	105	5.0	Transverse	--	29
	"	0.060	3.2	105	8.0	"	--	29
	"	0.060	3.2	105	7.0	Longitudinal	--	29
	"	0.093	3.3	105	9.0	Longitudinal and transverse	--	29
Inconel 718	Annealed	0.048	1.0	130	8.0	Longitudinal	--	41
	"	0.048	0.65	130	5.0	Transverse	--	41
	"	0.048	1.0	130	4.0	"	--	41
Waspaloy	Solution treated	0.063	0.5	180	--	Longitudinal and transverse	R_C 21	37
	Solution treated and aged	0.063	3.5	180	--	Ditto	R_C 36	37
M-252	Mill annealed	0.060	0.5	180	--	"	--	38
Hastelloy R-235	Mill annealed	0.063	0.5	180	--	"	--	39
René 41	Solution treated	0.025	2.0	130	9.0	Longitudinal	--	40
René 41	Solution treated	0.063	1.25	130	28.0	"	--	40

René 41 appears to be one of the more difficult alloys to form by bending. Springback of 9 degrees for 0.025-inch-thick sheet and 28 degrees in 0.063-inch-thick sheet for a 130-degree bend were reported by workers at McDonnell (Ref. 40).

In production operations, an allowance for springback can be made by overbending and then permitting the bend to return to the desired angle. Handworking operations may be employed to produce exact shapes. Hot-forming methods are not used much with the nickel- and cobalt-base alloys since many of them are of the precipitation-hardening type.

Post-Forming Treatments. The usual requirements for post-forming operations might include deburring, thorough cleaning by vapor degreasing, and alkaline-cleaning methods; visual or penetrant inspection for cracks; shearing length or width when required; and pickling, washing, protective wrapping, and identifying. Often the parts also are annealed after the final bending operation.

Sometimes parts are aged after they have been formed in the solution-treated condition to obtain the desired strength properties. Such aging is done usually above 1200 F and generally is followed by suitable pickling, washing, and wrapping of parts. Descaling by vapor blasting after aging enhances the fatigue life of specimens of Inconel X-750. Since the nickel-base alloys generally work harden to a greater extent than the austenitic stainless steels, intermediate anneals may be required especially if the final part shape requires extensive bending. These anneals are accomplished by heating in air at the solution-treating temperature to restore full ductility to the part. Such anneals must usually be followed by a pickling treatment to remove the scale that formed during the anneal.

If the dimensions and accuracy of the finished piece make the final anneal impractical, the following alternative procedure may be used:

(1) Form to as near completion as possible, preferably a minimum of 90 per cent of the finished shape

(2) Anneal at the solution-treating temperature

(3) Pickle

(4) Perform final sizing operations.

DEEP DRAWING

Introduction. Deep drawing is a process used to produce cylindrical or prismatic cups, with or without a flange on the open end, from sheet metal. Cups or tubes can be sunk or redrawn to increase their length and to reduce their lateral dimensions. These types of operations are illustrated by the six-stage drawing of Monel 400 cups in Figure 16. The drawing stresses result principally from the action of the punch on the central section of the blank. If the ratios of the blank diameter to sheet thickness and punch diameter are sufficiently small, the metal will draw in around the punch without buckling. Under such conditions, and by using other expedients, sheet metals can be deep drawn in single-action presses. Double-action presses, however, are used more often. They apply pressure on a blank holder to prevent buckling in the flange.

FIGURE 16. MULTIPLE-STAGE CUP DRAWING OF MONEL 400 ALLOY FROM 0.064-INCH-THICK SHEET

Courtesy of The International Nickel Company.

The deep-drawing process is well suited to producing large numbers of identical, deeply recessed parts. Precise tooling and carefully controlled forming conditions must be used to insure successful operations. The expense of setting up suitable equipment and procedures usually limits economical operations to rather large lots, over 500 pieces.

Nickel-base and cobalt-base alloys normally are deep drawn commercially at room temperature. Cups, domes, cones, and boxes are produced by deep drawing.

Presses for Deep Drawing. Both mechanical and hydraulic presses are used for deep drawing. The punch speed and the force available on a mechanical press ordinarily varies during the stroke. Furthermore, it is more difficult to provide a controlled blank-holder pressure on mechanical presses than on hydraulic presses. For these reasons, the use of mechanical presses is normally restricted to shallow parts where the depth of draw is 5 inches or less.

Hydraulic presses operate at lower punch speeds than mechanical presses. This is sometimes an advantage in deep drawing depending on the particular alloy. Hydraulic presses for drawing operations are generally equipped with a die cushion that is operated hydraulically. The hold-down pressure on the blank holder is normally preset to remain constant during the drawing operation although auxiliary pumps are sometimes used to vary the pressure during the stroke.

The blank holder must be constructed and adjusted to allow the metal to thicken as the edge of the blank moves radially toward the punch. The pressure needed to prevent wrinkling in the flange is of the order of 1-1/4 per cent of the ultimate strength of the workpiece material. This pressure, ranging from 500 to 2000 psi for nickel- and cobalt-base alloys, is exerted on the area of the blank holder in contact with the blank. It normally raises the drawing load by about 20 per cent. The hold-down pressure can be applied to the blank holder by air or hydraulic cushions or springs. Devices for this purpose can be added to single-action presses.

Presses are available in various sizes for deep drawing parts as small as cooking utensils and as large as automobile roofs. The characteristics of a few commercial presses used for typical operations are indicated in Table XV. Figure 17 shows an 800-ton hydraulic press equipped with a 600-ton die cushion used in forming sinks from stainless steel.

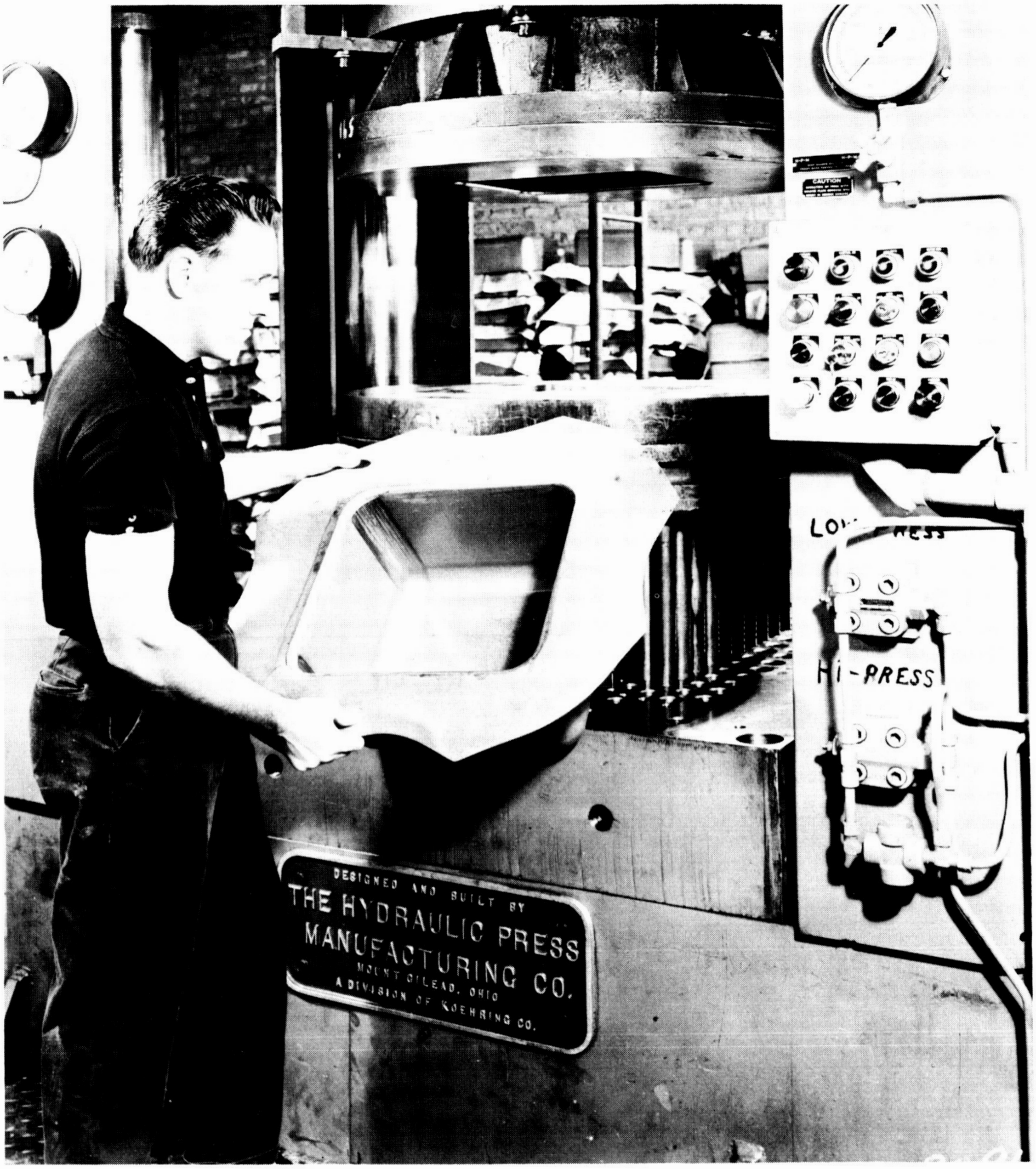


FIGURE 17. AN 800-TON PRESS EQUIPPED WITH A 600-TON DIE CUSHION USED FOR DRAWING STAINLESS STEEL SINKS

Courtesy of H. P. M. Corporation.

TABLE XV. CHARACTERISTICS OF TYPICAL DEEP-DRAWING PRESSES

Manufacturer	Type Press	Platen Size, in.	Tonnage
E. W. Bliss Company	Mechanical single-action air die cushion	24 x 24	100
		120 x 72	1200
	Mechanical double-action toggle press	24 x 24	100
		120 x 72	1200
H. P. M. Corporation	Hydraulic triple or single action with die cushion	36 x 36	150
		36 x 36	300
		60 x 48	400
		60 x 60	800
		60 x 60	1000
		72 x 72	2000

Notes:

(1) Most draw presses are single action with a die cushion. Some may require the use of an ejector for part removal.

(2) Increased platen area is generally coincident with increased press tonnage.

(3) Mechanical presses are more adaptable to high-speed and automated operation. They are also more difficult to control and tool up.

(4) Additional sizes and tonnages of presses are available, and the manufacturers should be consulted for specific requirements.

The maximum load in drawing a blank is normally reached when the flange has decreased in diameter by about 15 per cent or when the punch travel is about one-third complete. The maximum drawing load can be estimated from the following formula (Ref. 42):

$$P = \pi d T S (C - 1 + D/d) \quad , \qquad (11)$$

where

P = punch load, pounds

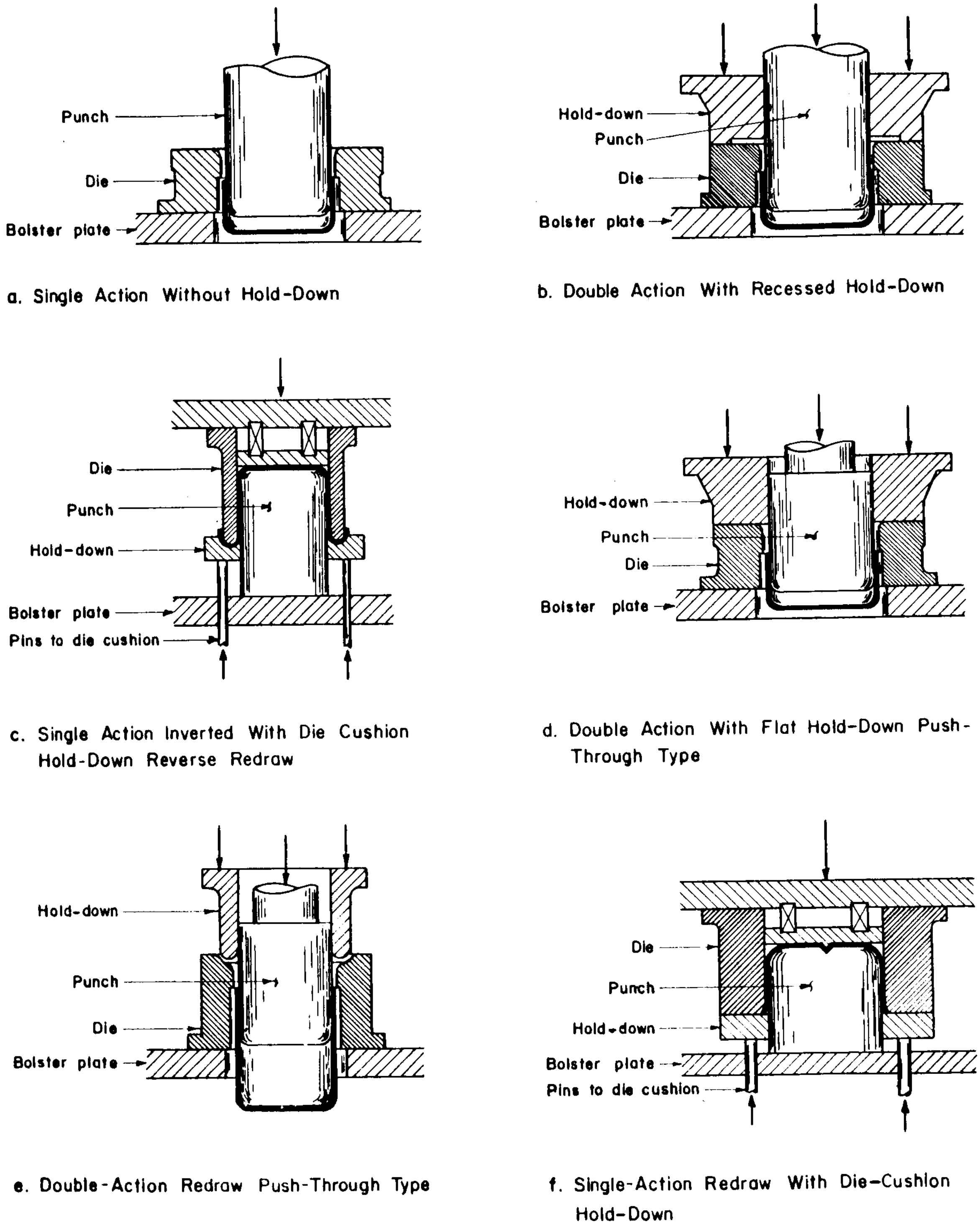
D = blank diameter, inch

d = punch diameter, inch

T = blank thickness, inch

S = maximum stress in metal, psi

C = an empirical constant to take bending and blank-holding loads into account; approximately 0.35 for nickel- and cobalt-base alloys.



a. Single Action Without Hold-Down

b. Double Action With Recessed Hold-Down

c. Single Action Inverted With Die Cushion Hold-Down Reverse Redraw

d. Double Action With Flat Hold-Down Push-Through Type

e. Double-Action Redraw Push-Through Type

f. Single-Action Redraw With Die-Cushion Hold-Down

FIGURE 18. TYPES OF DEEP-DRAWING OPERATIONS (REF. 44)

Tooling. The design of the tooling used in deep drawing depends on the type of press to be used. Some of the typical tooling arrangements for drawing or redrawing are shown in Figure 18. In the simplest terms, the tooling consists of three parts: the die, punch, and hold-down ring. The punch may be attached to the ram or, in inverted drawing operations, to the base platen. The die will be attached to the press member opposite the punch. The hold-down ring would be attached to the die cushion in an inverted operation by means of pusher rods or might be connected directly to a die cushion that can pull down instead of push. In single-action presses, an air-operated die cushion might be used or the hold-down ring might be attached to the ram and spring loaded. When the depth of draw to the blank-diameter ratio is small, it is sometimes possible to form without the use of a hold-down ring. An example of this is shown in the tool used to form Inconel domes illustrated in Figure 19.

FIGURE 19. DRAWING A DOME FOR A NEUTRAL SALT POT MADE OF INCONEL ON A SINGLE-ACTION PRESS

No hold-down was required.

Courtesy of California Alloy Products Company.

Although not widely used in production operations, there are two alternative methods for preventing wrinkling without supplying controlled pressures to the hold-down ring. A rigid blank holder with a flat surface is the simplest type of hold-down ring. It requires careful adjustment of the gap between the die and the hold-down surface to allow for thickening as the blank is drawn and to prevent wrinkling. The drawing load is increased when the gap is either too small or too large. According to Sachs (Ref. 44), the gap should be 25 to 50 per cent smaller than the thickness developed as the edge of the flange moves from its origin to final position. This amount of thickening is given by the equation

$$T/T_1 = D/D_1 \quad , \tag{12}$$

where

T = blank thickness

T_1 = thickness of the flange during drawing

D = blank diameter

D_1 = diameter at the edge of flange or the mean diameter of cups drawn without a flange.

The difficulty of adjusting rigid blank holders can be avoided by tapering the hold-down surface. The taper, which is not very critical, can be based on Equation (12). Experiments indicate that conical blank holders result in lower drawing loads than other types (Ref. 44).

A number of tooling materials have been used for deep drawing nickel- and cobalt-base alloys at room temperature. Some of these materials, starting with the shortest life, are gray cast iron, cast semisteel, hard-alloy bronze, heat-treated nickel-chromium cast iron, chromium-plated hardened steel, and tungsten carbide. Carbon-steel dies should be avoided because of a tendency to gall. The punches are generally chromium plated 0.0002 to 0.0004 inch for easier removal of the part from the punch.

Clearances between the punch and die must be controlled to prevent galling, rupture, or buckling in the cup wall. The selection of the clearance between the punch and draw ring depends to some extent on the dimensional requirements of the part. If the clearance is larger than the amount of thickening predicted by the preceding equation, the cupped part will not be in contact with both the punch and the die. This permits a minimum drawing load but results in a part with a variable wall thickness. If the clearance is smaller than necessary to accommodate the thickening in the upper part of the cup, some ironing or wall thinning will occur. Severe ironing increases drawing loads. Clearances for deep drawing nickel and cobalt alloys may be slightly less than those used for mild steel. This is because these alloys generally possess higher physical properties than drawing-quality steel and have greater resistance to wall thinning. For deep drawing cylindrical shells, clearances of 40 to 50 per cent greater than the metal thickness should provide parts without ironing or wrinkling from sheet of less than 0.064 inch. Greater clearance should be used for thicker sheet.

The radii on the draw ring and nose of the punch are important in severe drawing operations because they affect the stress required for bending. If the punch radius is too small, the metal will thin, neck, and rupture near the bottom of the cup. Radii slightly larger than the minimum allowed for bending will permit shallow draws. Larger radii permit parts to be formed with larger flanges or to deeper depths. In general, the radius on the draw ring should be 5 to 12 times the thickness of the metal (Ref. 30). Excessively large radii, in excess of about 15 T, may cause the parts to pucker. For severe operations, the punch radius should exceed 5 times the sheet thickness. When multiple-stage drawing is to be performed, large draw-ring radii should be used on the initial die stages. The radius can be reduced on the final stages until the desired radius is obtained.

Techniques for Deep Drawing. The techniques used in deep drawing depend on the type of equipment available and the shape of the part to be produced. Shallow parts of cylindrical shape are the easiest to produce; as the complexity of shape and depth of draw increase so does the difficulty in setting up and producing the parts. In most drawing operations, compressive stresses in the circumferential direction tend to buckle or wrinkle the rim of the blank. Shallow wrinkles can be ironed out between the punch and the die, but they should be prevented from forming by adjusting the force on the hold-down ring. For large production runs on a single-action press, the clamping force may be applied by means of springs. Where production runs are smaller, or a number of different size parts are to be made on the same equipment, it is better to have a readily adjustable hold-down force. This is a desirable feature when variations in thickness and properties of sheet material might be expected. The operator can readjust the machine settings to accommodate the variations and reduce the amount of scrap. The double-action press is more versatile with respect to adjustment of operating conditions, but may be more expensive to tool up.

Some parts may be deep drawn in one stroke of the press; others require a number of operations in different dies. There is a limit, even with intermediate anneals, on how far a part can be reduced in one set of dies. The general practice is to take smaller reductions in redrawing operations than that used for the previous operation. A 35 to 40 per cent diameter reduction on cupping should be reduced to 15 to 25 per cent on redraw. A multistage drawing sequence of nickel is shown in Figure 20. Two intermediate anneals were required in forming this cup.

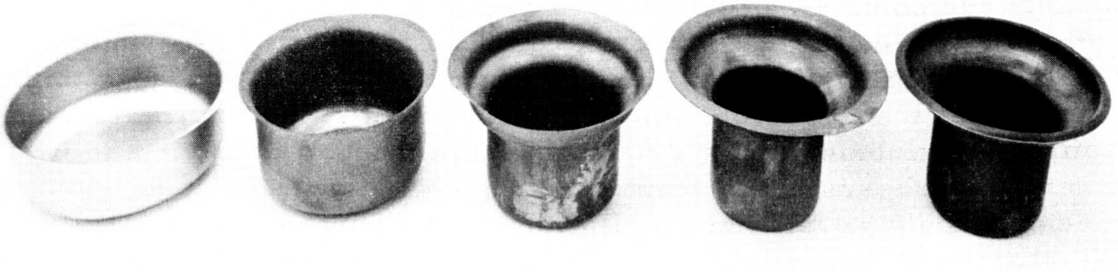


FIGURE 20. MULTISTAGE DRAWING OF PURE NICKEL FOR MAKING A LINER IN A SOAP CUP

Courtesy of Liberty Electric Company.

The depth to which the nickel- and cobalt-base alloys can be drawn for making rectangular shapes in one press stroke is a function of the corner radius. The corner radius should, therefore, be as large as possible to avoid difficulty. The depth of draw for Monel and nickel should be limited to 2 to 5 times the corner radius. Four times the corner radius should be the limit for Inconel 600. Such factors as the shape of the part, whether it has straight or tapered sides, and the thickness of material affect the limiting depth of draw. As the thickness decreases below 0.050 inch, the permissible depth also decreases. For instance, three times the corner radius should be the limit for depth of draw on 0.025-inch-thick Monel 400, Nickel 200, and less for Inconel 600.

The draw-ring radius should be more generous for drawing rectangular shapes than for cylindrical shapes. A factor of 4 to 10 times the thickness of the material should be used.

Rectangular shapes can be redrawn to sharpen the corners or to stretch out wrinkles along the sides. When the depth of draw is greater than that possible in one operation, it is sometimes possible to draw about two-thirds of the depth in the first pass, anneal the part, and complete the part in the same die. This practice is also used to avoid wrinkling.

Lubrication of the blanks in deep drawing is necessary to obtain maximum drawability. Lubricants minimize the energy required to overcome friction between the blank and the tooling and reduce the possibility of galling or seizing.

Fatty oils are often satisfactory lubricants for drawing nickel and cobalt alloys, but the pigmented types are preferred. Most of the nickel- and cobalt-base alloys require more hold-down pressure than for drawing steel or the softer metals. Consequently, it is important to use a lubricant with high-film-strength lubricity and good wetting characteristics to prevent galling. An inert filler is used in most satisfactory lubricants for drawing nickel or cobalt alloys. The various manufacturers of lubricants should be contacted for specific recommendations for a given alloy and type of drawing. The use of lubricants containing lead or sulfur should be avoided if the parts are to be given a thermal treatment after forming. All lubricants should be thoroughly removed before any thermal treatment of nickel or cobalt alloys.

Some of the nickel-base alloys are available in the form of strip 0.156 inch thick or less, with a copper flash on the surface. These alloys include Nickel 200, Monel 400, and Inconel 600. The copper flash serves as a lubricant in deep drawing.

In some cases, applying the lubricant to only certain portions of the blank or tooling may assist in obtaining maximum formability. For instance, a lubricant between the blank and the die and the blank holder, and between the part and the die is desirable. Friction in those locations raises the drawing load and may lead to galling or nonuniform movement of material over the tooling. On the other hand, friction at the radius and bottom of the punch is desirable. Higher friction on the punch side of the blank reduces the tensile stresses that cause stretching, and sometimes rupture, at those locations. Therefore, benefits are sometimes obtained from rough or unlubricated punches (Ref. 45).

<u>Principles of Deep Drawing</u>. Failures in drawing operations result from complex phenomena. Unlike the situation in some other forming operations, failure conditions are controlled by the general change in shape rather than by the strain requirements in certain locations. The forces developed at the punch originate from:

(1) The stress required to bend the sheet around the nose of the punch

(2) The stress necessary for circumferentially compressing and radially stretching the metal in the flange

(3) The stress required to bend the metal around the draw ring and unbend it as it flows from the flange into the wall of the part

(4) The stress used in overcoming friction at the die radius and under the blank holder

(5) The stress developed by ironing the wall.

For these reasons, it is difficult to predict success or failure in a particular deep-drawing operation from ordinary tensile data for the workpiece materials.

A considerable background of information is available about the influence of characteristics determined in true-stress true-strain tensile tests on the performance of steel in deep-drawing operations. Although the principles would be expected to hold for nickel- and cobalt-base alloys, pertinent data are sparse. Studies on steel indicate that better performance in drawing operations correlates with higher values of work-hardening coefficients and uniform elongation and more severe "normal" anisotropy. The relative importance of these characteristics varies with the geometry of the drawing operation.

Uniform elongation is particularly important in drawing operations characterized by significant amounts of stretch forming. For example, it is more important in controlling forming limits for cups with hemispherical rather than flat bottoms. Even when stretching is not of major importance the workpiece must be ductile enough to withstand bending. Higher work-hardening coefficients indicate resistance to thinning and permit deeper draws without tearing.

The concept that pronounced normal anisotropy is desirable for deep drawing is a little more complicated. For maximum drawability in ductile metals it is desirable for the material to be resistant to thinning from radial stretching but weak in upsetting from circumferential compression. This results in a high strength in the wall of the cup compared with the stresses needed to upset material in the flange. This condition is better satisfied by materials exhibiting higher ratios of width-to-thickness strains in tensile tests. This type of anisotropy termed "normal" in contrast to directional variations in properties in the plane of the sheet is expressed by the following relationship:

$$R = \frac{\ell n \; W_o/W}{\ell n \; T_o/T} \quad , \tag{13}$$

where

R = anisotropy ratio

W_o = original width of specimen

W = width after straining

T_o = original thickness

T = final thickness.

The anisotropic parameter of a sheet material can be determined by measuring strain ratios of specimens oriented at 0, 45, and 90 degrees from the rolling direction. The component of normal anisotropy can be defined as:

$$R = 1/4\ (R_0 + 2\ R_{45} + R_{90}) \quad . \tag{14}$$

The degree of normal anisotropy in terms of relative flow strengths in the thickness, Z, and planar, X, directions of sheet is given by the expression

$$\frac{Z}{X} = \sqrt{\frac{1 + R}{2}} \quad . \tag{15}$$

A completely isotropic material would have R values of one, for tests in all directions, and a uniform strength in the thickness and plane of the sheet.

The severity of a deep-drawing operation can be described by defining the geometry of the cup and blank. The important geometric variables are indicated in Figure 21. The deep-drawing properties of materials are often compared on the basis of the maximum reductions they will withstand under standardized conditions. The ratings are often expressed on the basis of the

$$\text{Maximum Drawability Percentage} = 100 \times \frac{D-d}{D} \quad ,$$

or the

$$\text{Limiting Drawing Ratio} = D/d \quad ,$$

where D and d are the diameters of the die and punch, respectively.

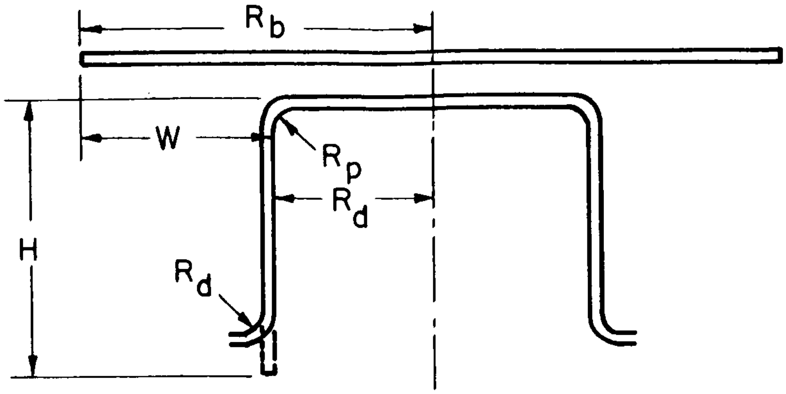


FIGURE 21. GEOMETRICAL VARIABLES FOR CUPPING (REF. 33)

R_b = radius of the blank
R_d = radius of the die
$W = R_b - R_d$
H = finished height of cup with no flange
R_p = radius of the punch
$D = 2\ R_b$ = blank diameter
$d = 2\ R_d$ = punch diameter.

The ratio of the blank radius to the height of the cup is also used to indicate the severity of a drawing operation. The height, H, of flat-bottomed cups with sharp radii, and if no stretching or ironing occurs, can be calculated from the relationship:

$$H/d = 1/4 \left[(D/d)^2 - 1 \right] \quad . \tag{16}$$

When there is a flange on the cup, the relationship changes as shown in Figure 22. As an example, the difference between a good part and a split part was the use of a flange on the Monel shells shown in Figure 23. The ratio of the diameter or radius to the thickness of the blank may affect success in deep drawing. In any case, the friction resulting from the hold-down pressure becomes an appreciable part of the load in drawing comparatively thin blanks.

Nickel- and Cobalt-Base-Alloy Deep-Drawing Forming Limits. As with most forming operations, sufficient ductility must be available in the material for successful drawing operations. For instance, in attempts to draw a 5-inch-diameter cup 5.5 inches deep from a hard and a soft Monel blank, the hard blank split while the soft blank could be formed to the desired shape satisfactorily.

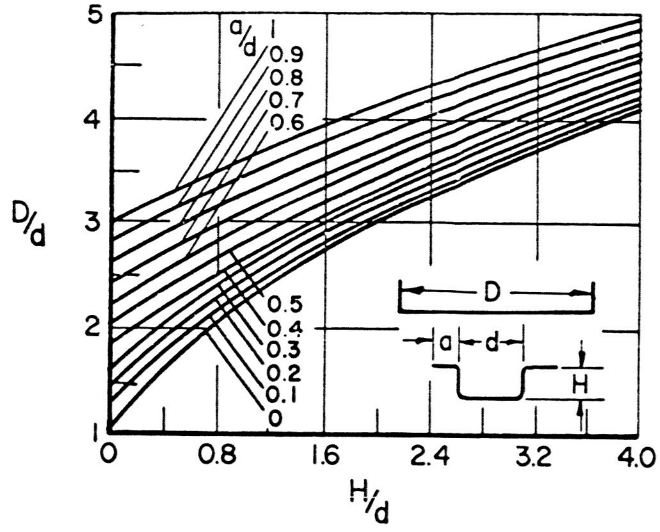


FIGURE 22. THEORETICAL RELATIONS BETWEEN DIMENSIONS OF SHARP-RADIUSED CYLINDRICAL PART AND BLANK DIAMETER (REF. 44)

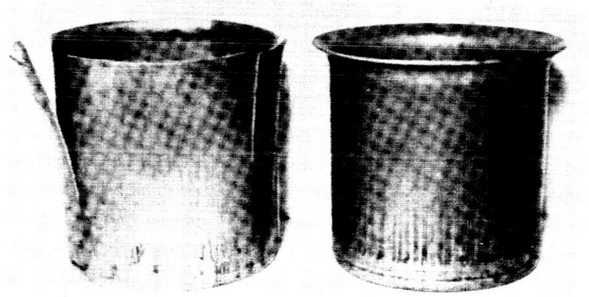


FIGURE 23. MONEL SHELLS DEEP DRAWN FROM HARD BLANKS WITH AND WITHOUT A FLANGE

5-inch diameter and 5-inch depth made in three draws with no intermediate anneals. Courtesy of The International Nickel Company.

Wood and associates (Ref. 33) have indicated that drawability of the material can be determined by the following forming index:

$$\frac{E}{Y_c} \times \frac{Y_c}{Y_t} = \text{Deep Drawing Formability Index} \quad , \qquad (17)$$

where

E = Young's elastic modulus, psi

Y_c = compressive yield strength, psi

Y_t = tensile yield strength, psi.

An increase in index indicates an increase in formability in deep drawing. Using this index for a particular material and material condition, a relationship between the flange-width to part-radius ratio and flange-width to material-thickness ratio can be determined and a forming limits envelope, as shown in Figure 24, can be constructed. René 41 appeared to have the best drawability at 400 F, while L-605 alloy showed very little change in drawability with temperature. The forming limits in Figure 24 show the small change in drawability with increasing temperature for the alloys. This is basically why most of the nickel- and cobalt-base alloys are deep drawn at room temperature.

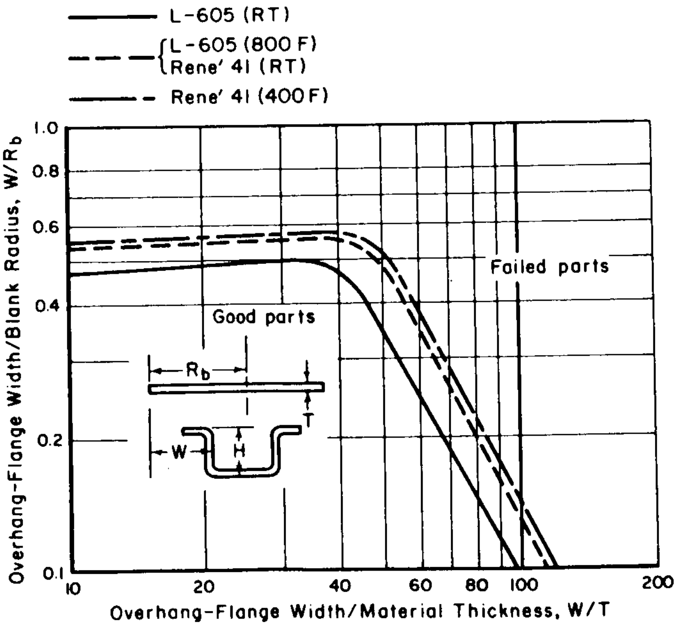


FIGURE 24. DEEP-DRAWING-LIMIT CURVES FOR L-605 AND RENÉ 41 AT ROOM TEMPERATURE AND ELEVATED TEMPERATURES (REF. 33)

Post-Forming Treatments. The post-forming treatments of deep-drawn nickel- and cobalt-base parts are the same as those for other cold-worked components. Sometimes the parts can be trimmed in the forming die, but this generally increases die costs.

The residual lubricants from the drawing operation should be removed completely from the part before it is given any thermal treatment.

SPINNING AND SHEAR FORMING

Introduction. Spinning and shear forming are processes for shaping seamless, hollow sheet-metal parts by the combined forces of rotation and pressure. Only minor changes in material thickness occur during spinning; shear forming causes thinning.

Shear forming differs from spinning principally because it produces reductions in thickness. A number of trade names have been used to describe the shear-forming process, since its development. Some of the nonproprietary names used in the past are roll forming, rotary extrusion, shear spinning, flow turning, and power spinning. Throughout this report, the term shear forming will be used because it appears to be emerging as the most accepted name for the process.

Principles of Spinning. Spinning may be classified as manual or power spinning depending on the manner of applying the force to the blank. Manual spinning, illustrated in Figure 25, is limited to thin (less than 1/16 inch thick) low-strength (yield strength under 30,000 psi) workpieces. Power spinning uses mechanical or hydraulic devices to apply greater tool forces to the blank and can consequently be used to form thicker and stronger materials.

Spinning differs from most metalworking processes in that the material is deformed at a point rather than over a broad area, and a large portion of the blank is unsupported during processing. These characteristics are advantageous in such operations as internal spinning where simple tooling can be used to make complex shapes. The application of internal spinning is shown in Figure 26.

During spinning the metal blank is subjected to bending forces along the axis of spinning and compression forces tangential to the part. Difficulties are encountered with elastic buckling when the ratio of the depth of the spun part to the thickness of the metal becomes too great. The limits are related to the ratio of compressive modules of

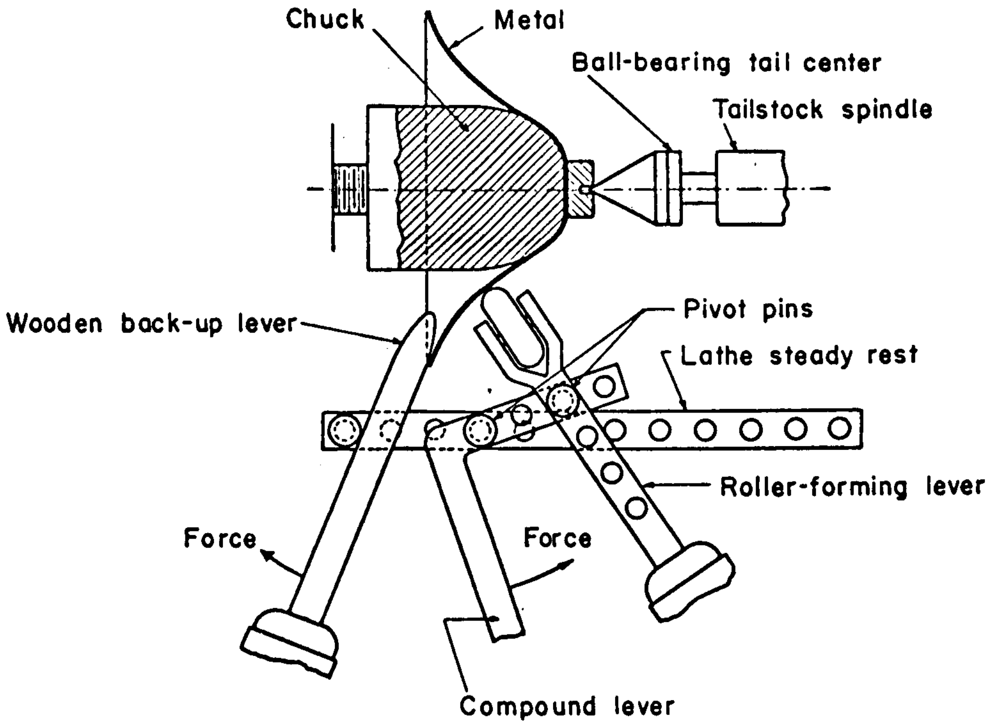


FIGURE 25. MANUAL SPINNING (REF. 43)

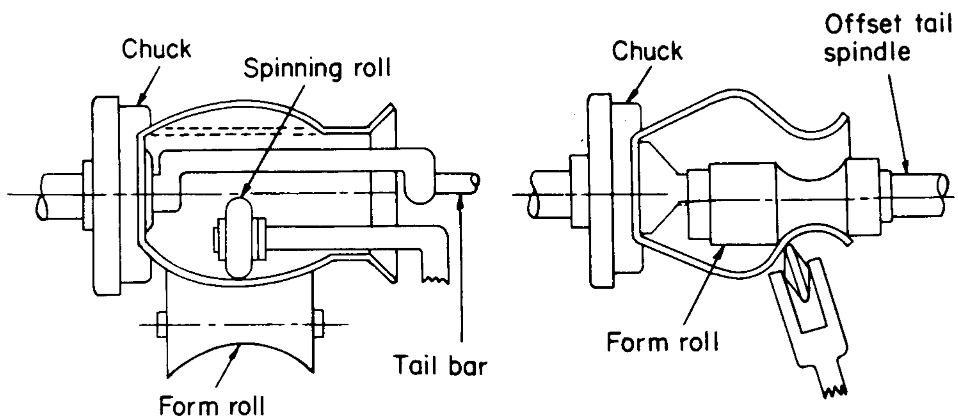


FIGURE 26. INTERNAL SPINNING TECHNIQUES (REF. 46)

the material to the compressive yield (Ref. 25). Elastic buckling occurs in the unspun flange of the part as shown in Figure 27.

The ratio of depth to diameter of parts that can be produced by spinning is limited by plastic buckling. Buckling limits are related to the ratio of tensile modulus to the tensile ultimate strength of the workpiece material (Ref. 25). Plastic buckling should be prevented, since it is difficult to remove, by limiting the amount of deformation in one operation to that permitted by the characteristics of the material. Most nickel and cobalt alloys are spun at room temperature since very little improvement in spinnability is obtained unless they are heated to very high temperatures.

Exceeding the formability limits can cause shear splitting or circumferential splitting, as shown in Figure 28. Shear splitting is the result of exceeding the ultimate tensile strength of the material in the tangential direction, while circumferential splitting is caused by exceeding the tensile ultimate strength of the material in the axial direction.

Spinning to the final shape desired may require a number of steps and intermediate anneals between them. The amount of reduction taken in each successive step should be reduced for a successful operation. For example, a part that receives 50 per cent reduction on the first step might be reduced 40 per cent on the next step and 30 per cent on a final step. The amount of reduction that can be obtained in each step is a function of the work-hardening characteristics of the material. Typical reductions between anneals for nickel, Monel, and Inconel are shown in Figure 29.

Principles of Shear Forming. Shear-forming processes can be broken down into cone and tube shear forming; other shapes can be considered as modified cones.

A typical example of cone shear forming is shown in Figure 30. The blank, a circular disk, is clamped to the rotating mandrel by the tailstock. Two rollers located at opposite sides of the mandrel apply a force along the axis of the mandrel and force the blank to take the shape of the mandrel. Figure 30 shows a progression of the forming sequence, starting from left to right. The rolls are not driven, but rotate due to contact with the rotating blank.

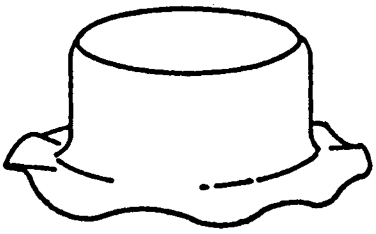


FIGURE 27. ELASTIC BUCKLING IN A SPUN PART (REF. 25)

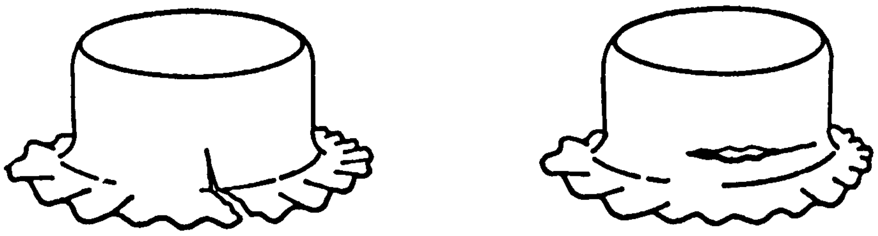


FIGURE 28. SHEAR SPLITTING AND CIRCUMFERENTIAL SPLITTING (REF. 25)

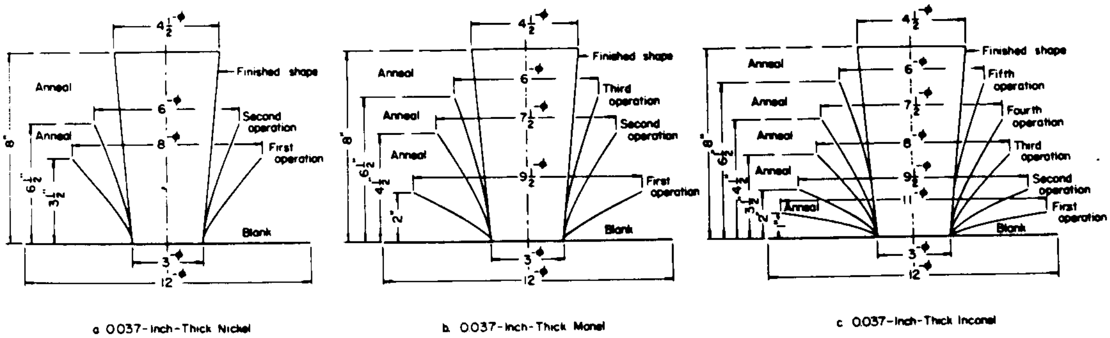


FIGURE 29. SPINNING STAGES REQUIRED TO FORM A 3-INCH-DIAMETER CUP
FROM 0.037-INCH NICKEL, MONEL, AND INCONEL (REF. 47)

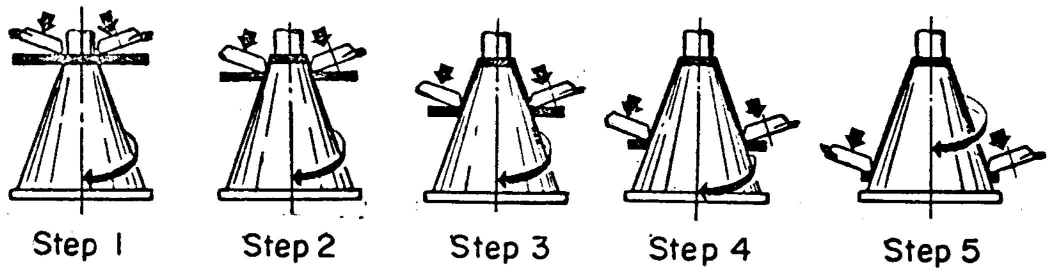


FIGURE 30. STEPS IN SHEAR FORMING A CONE (REF. 48)

Cone Forming. The percentage reduction of material thickness during cone shear forming is a function of the part shape. Figure 31 shows the geometric measurements that are important for shear forming a cone. The final thickness is related to the initial thickness of the blank by the sine of the half angle of the cone.

$$T = T_b \times \sin a/2 \quad , \qquad (18)$$

where

T = the final thickness, inches

T_b = the initial blank thickness, inches

a = the included angle of the cone, degrees.

The percentage reduction is therefore related to the sine of the cone half angle as

$$R = 100\ (1 - \sin a/2) \quad , \qquad (19)$$

where R = the per cent reduction.

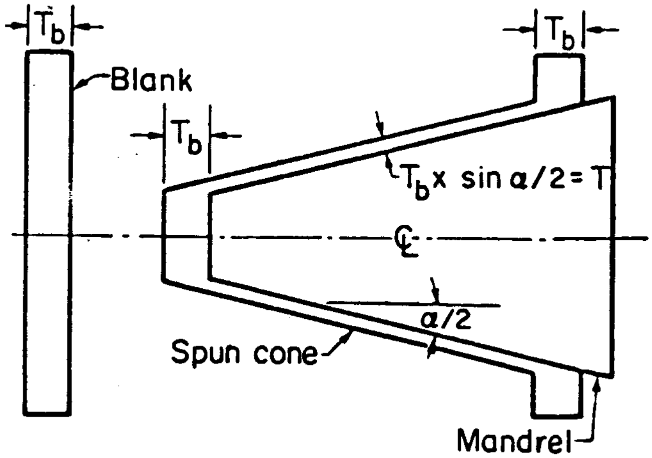


FIGURE 31. GEOMETRIC RELATIONS IN CONE SHEAR FORMING (REF. 49)

The same rule applies to shapes other than a cone, with the final thickness at any given point along the part being determined by the angle the part makes with the axis at that point. For instance, in a formed hemisphere, the bottom is the same thickness as the blank, whereas the edge is the thinnest section, as shown in Figure 32.

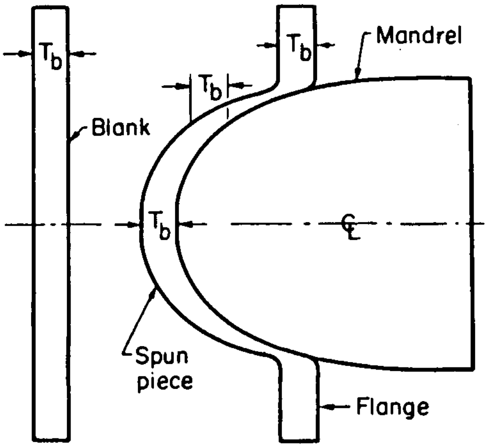


FIGURE 32. THICKNESS OF A MATERIAL IN A SHEAR-FORMED HEMISPHERE (REF. 49)

Tube Shear Forming. As shown in Figure 33, shear forming of tubes can be of two basic types: forward and backward. In forward tube shear forming the material flows in the same direction as the tool motion, usually toward the headstock. In backward shear forming the material flow is opposite the roller travel, usually toward the tailstock (Ref. 50).

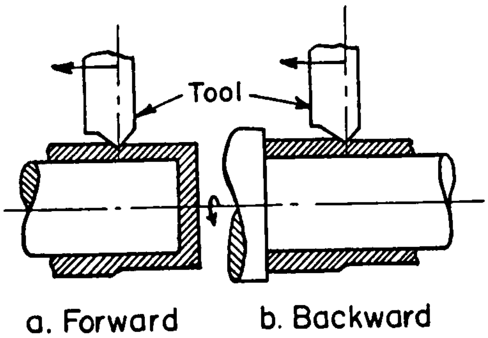


FIGURE 33. SCHEMATIC OF TUBE SHEAR FORMING (REF. 51)

Backward tube shear forming simplifies blank holding and can result in increased production since the tool travels only 50 per cent of the total part length. The process can produce parts that are beyond the normal length capacity of a specific machine. There are difficulties in backward shear forming with respect to holding axial tolerances. Since the first section of deformed material must travel the greatest distance it is most likely to be out of plane.

Forward tube shear forming has found wide acceptance where longitudinal accuracy of sculptured sections is required. Since each increment of material that is formed is not required to move, errors in concentricity are swept away from the finished part and are left in the trim stock.

In shear forming of tubing the basic sine law for shear forming cannot be applied. The maximum permissible reduction for ductile materials depends on the state of stress in the deforming area and the material properties. The maximum reduction can be predicted from the tensile reduction in area both for cone and tube shear forming (Ref. 52). The experimental data shown in Figure 34 indicate that a maximum spinning reduction of about 80 per cent is obtained at a tensile reduction in area of 50 per cent. Beyond this tensile reduction there is no further increase in formability. Among materials with a

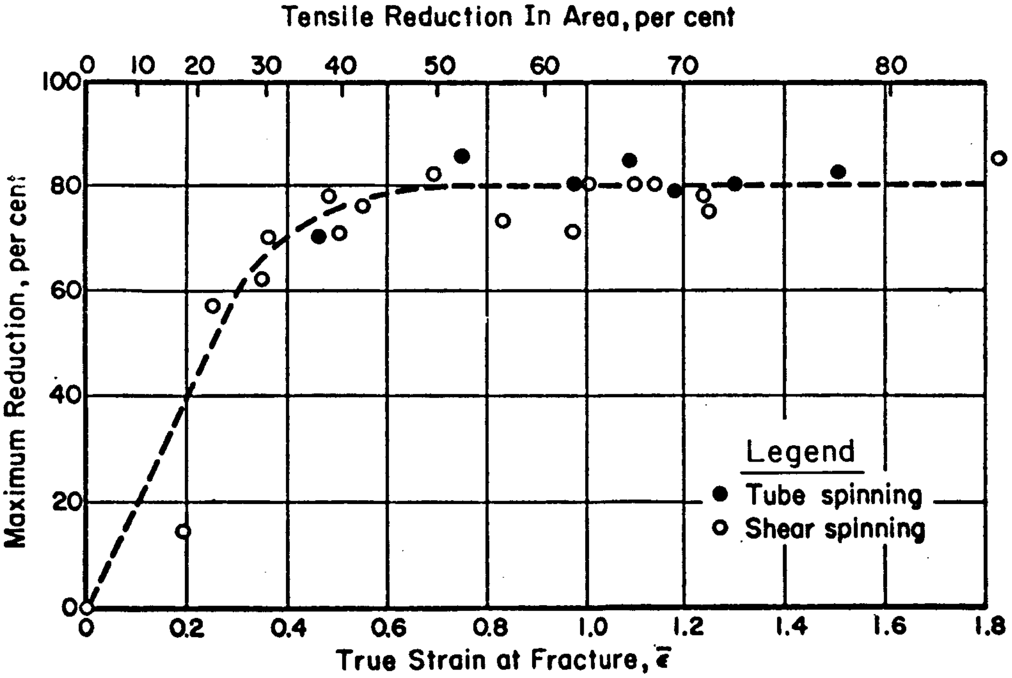


FIGURE 34. MAXIMUM SPINNING REDUCTION IN TUBE AND SHEAR SPINNING OF VARIOUS MATERIALS AS A FUNCTION OF TENSILE REDUCTION IN AREA (REF. 52)

reduction-in-area value less than 50 per cent ductility determines formability.

Some of the process parameters affecting the maximum reduction possible are the feed rate, corner radius of the tool, the depth setting of the tool, and the angle of the tool. In general, increase in feed or corner radius will decrease the maximum permissible reduction. The roller angle appears to have very little effect on the maximum reduction between 15 and 45 degrees. Beyond these limits the effects are not known.

Types of Equipment. Most engine-lathe manufacturers will make equipment for spinning. The manually operated machines have given way to the mechanically or hydraulically operated equipment. The latest equipment incorporates numerical control for automatic programming of the spinning operation.

Shear-forming machines are an extension of the capabilities of the spinning lathe. The machines are heavier and have considerably more power than the spinning lathes. Spinning can, however, be conducted on a shear-forming machine that can be used in the production of cones.

One of the large shear-forming machines is shown in Figure 35. Some specifications are given in Table XVI for machines manufactured by Lodge & Shipley, Cincinnati Milling Machine, and Hufford. Additional sizes of machines may be available so that the manufacturers should be informed of specific requirements. A typical shop layout for shear forming is given in Figure 36. Integration of the shear-forming process with other manufacturing would probably dictate other layouts.

Types of Tooling.

Tooling for Spinning. Planishers for manual spinning of nickel-base and cobalt-base alloys are generally made of hard alloy bronze to prevent gouging of the workpiece. The tools should be broader and flatter than those used for softer materials. For mechanical or hydraulic spinning, rollers of hardened tool steel with a hard chromium plate are used. The surface of the rollers or planishers should be highly polished. The diameter of the rollers in spinning is selected on the basis of the diameter of the part to be formed; the roller diameter should be approximately half the smallest diameter of the part.

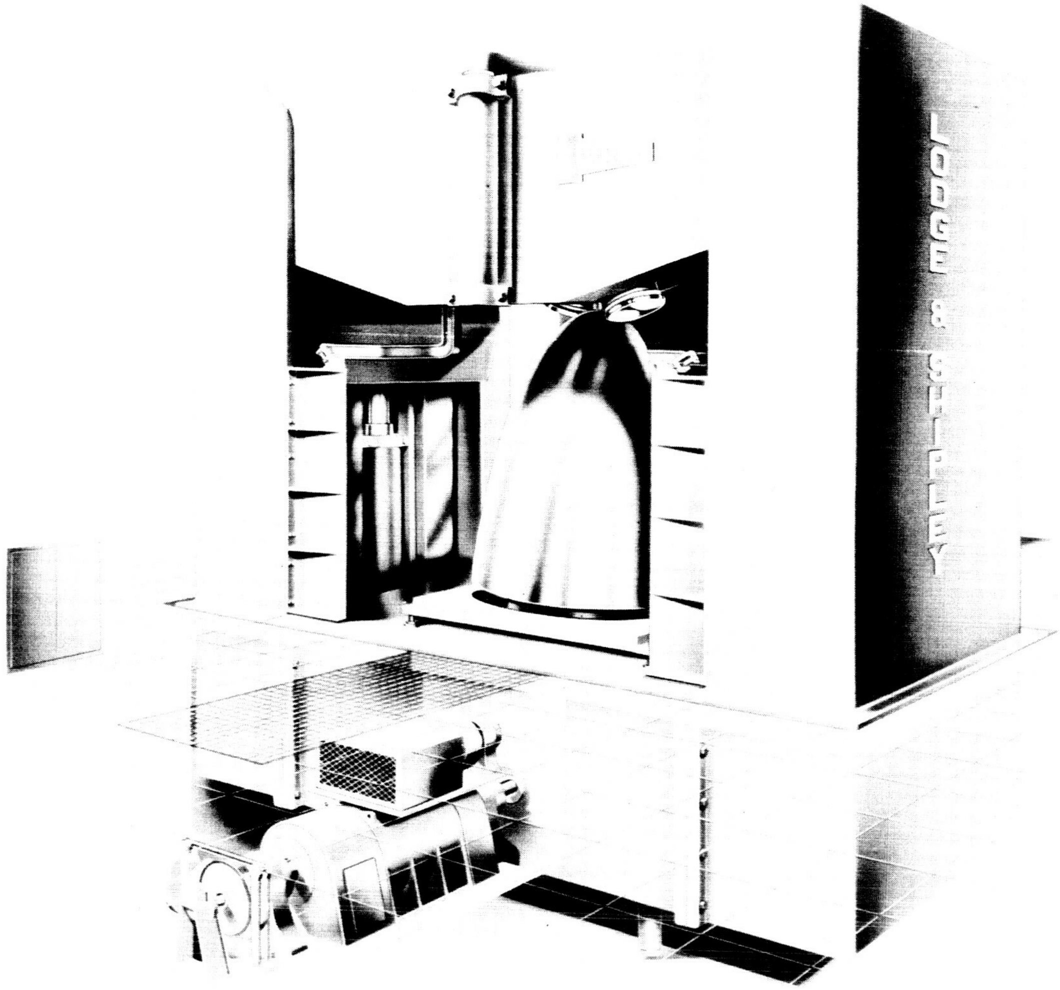


FIGURE 35. LODGE & SHIPLEY 60 INCH X 10 FOOT VERTICAL FLOTURN MACHINE (REF. 48)

TABLE XVI. TYPICAL AVAILABLE SPINNING AND SHEAR-FORMING MACHINE SIZES (REFS. 48, 53, 54)

Manufacturer	Port Diameter, inches	Port Length, inches	Spindle, hp	Forces: Roller, lb	Forces: Carriage, lb	Forces: Tailstock, lb	Production Rate, piece/hr	Machine Weight, lb	Number of Rolls	Type
Lodge & Shipley	12	15	15	4,000	5,000	2,000	75-100	8,750	1	Horizontal
Floturn	12	15	40	14,000	12,000	3,000	90-125	26,000	2	Vertical
	24	30	75	32,000	54,000	8,000	30-80	52,000	2	Vertical
	40	50	20	15,000	--	7,500	8-30	41,000	1	Horizontal
	60	70	90	40,000	--	15,000	1-15	100,000	1	Horizontal
	70	84	150	70,000	70,000	35,000	1-15	195,000	2	Horizontal
Cincinnati Milling	42	50	20	50,000	50,000	35,000	--	53,970	1	Horizontal
Machine Company	42	50	20	50,000	50,000	35,000	--	78,970	2	Horizontal
Hydrospin	62	50	20	50,000	50,000	35,000	--	145,500	2	Horizontal
	70	72	30	70,000	70,000	50,000	--	235,000	2	Vertical
Hufford	60	60	200	225,000	225,000	200,000	--	--	2	Vertical
Spin forge	60	120	200	225,000	225,000	200,000	--	425,000	2	Vertical

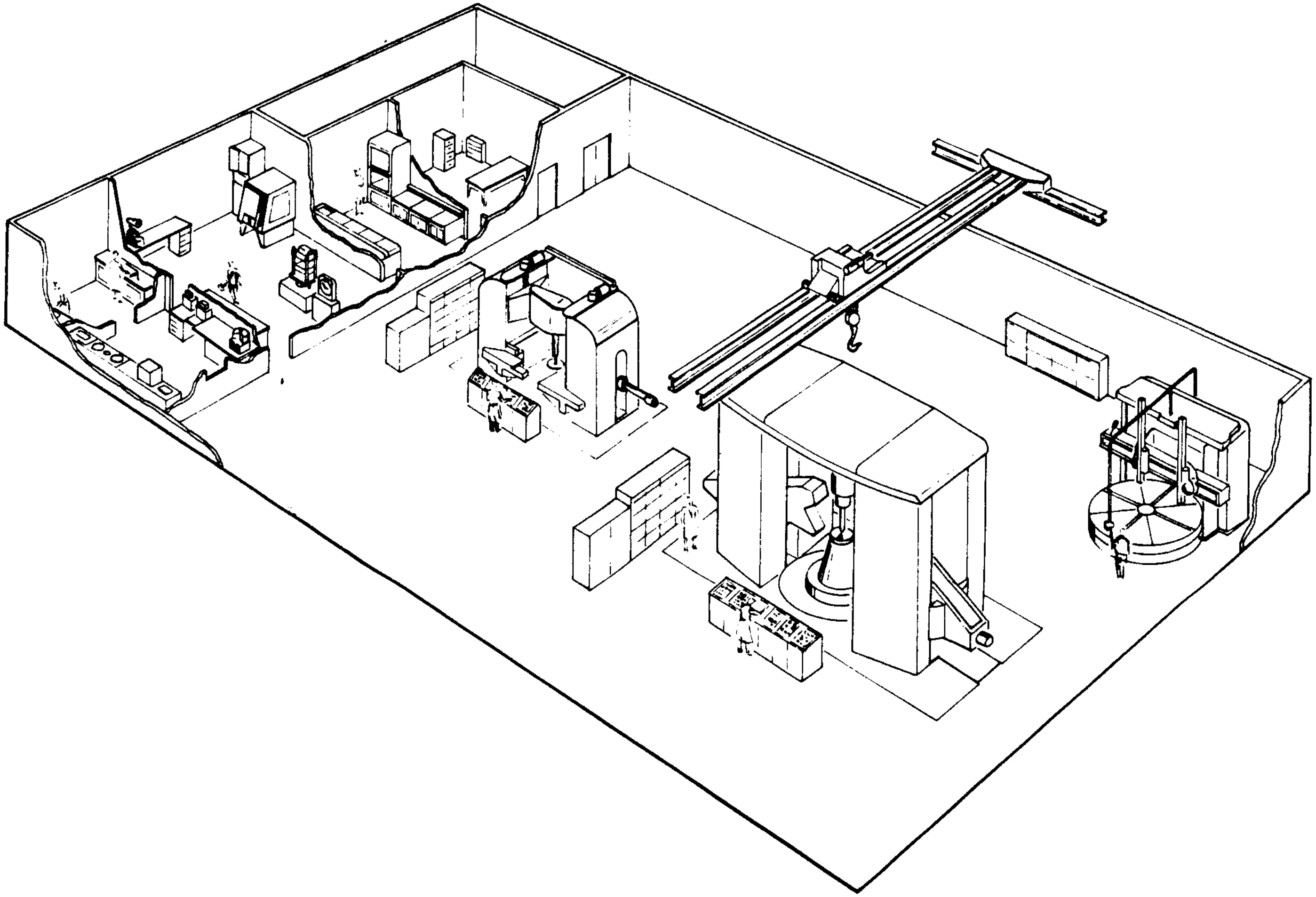


FIGURE 36. TYPICAL SHOP LAYOUT FOR SHEAR FORMING

Courtesy of Hufford, El Segundo, California.

Mandrels or chucks for spinning can be made of wood such as hard maple or birch, or plastic for production runs of 25 parts or less. These are generally used for intermediate operations where tolerances are liberal. For greater production the mandrels may be made of ductile cast iron or tool steel. A hard, smooth surface on the mandrel permits the removal of tool marks from previous forming stages and gives a closer tolerance on the finished part. The mechanical properties of the nickel and cobalt alloys will generally result in a greater periphery than softer materials spun on the same mandrel. The mandrels should, therefore, be slightly under size compared with those used to spin the same part in copper.

Tooling for Shear Forming. Shear forming requires stronger tooling than spinning because greater forces are characteristic of the process. Rollers are used for applying the forming force to the blank. The diameter of the rolls is generally kept to a minimum consistent with the force it is required to transmit. A smaller roller has less contact area with the blank and consequently less friction and power loss. The shape of the roller depends on the amount of reduction to be taken with each pass. A typical roller configuration is shown in Figure 37 and the more important surfaces are indicated. The contact angle determines the length of contact surface for any given reduction. The greater the contact length the greater the frictional forces between the roller and the metal. The approach surface and contact angle are required to prevent the material from burring ahead of the roller. Since the roller step controls the amount of reduction, a different roller is required for each reduction. The burnishing angle and land tend to smooth out the ring marks left on the part due to the axial travel of the tool. Rollers for shear forming are generally made of high-speed tool steel heat treated to R_C 60. The surface is polished and can be hard chromium plated for a good surface finish on the part.

The mandrels for shear forming are made of heat-treated steel because of the high forces involved. A softer material would be locally deformed by the roller pressure. Large mandrels are generally made as shells with supporting internal structure while smaller mandrels are solid.

Heating Methods. For elevated-temperature spinning or shear forming, the mandrels are generally heated. This can be accomplished by electric-resistance cartridges or by flames. The electric-resistance method may be more expensive to operate but provides less opportunity for contamination of materials that tend to

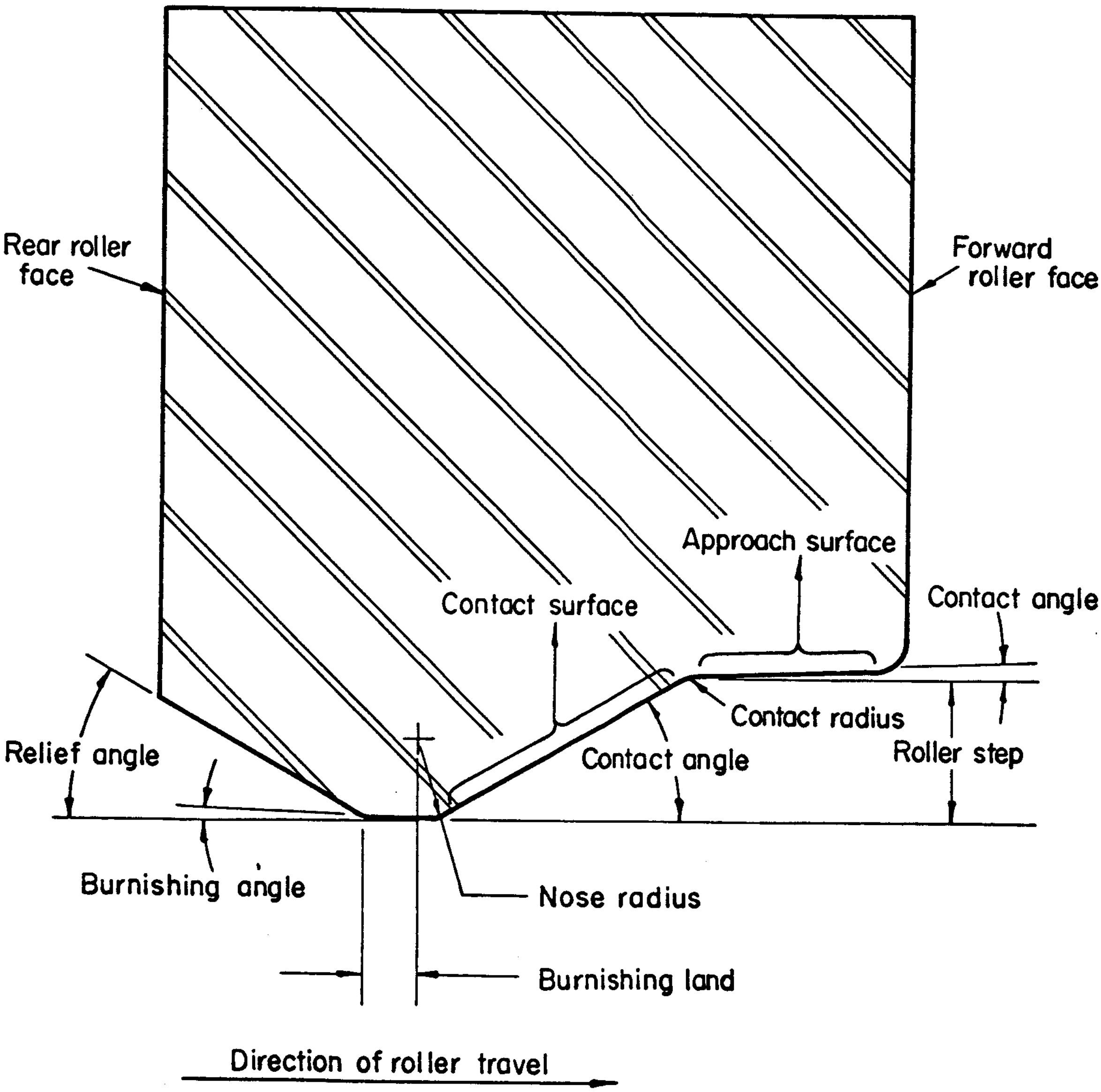


FIGURE 37. ROLLER CONFIGURATION FOR SHEAR FORMING (REF. 55)

oxidize readily. The rotating contacts transmitting current to the mandrel sometimes limit the amount of power that can be used.

Flame heating of the mandrel can be accomplished with natural gas or bottled gas. For this practice, mandrels are generally hollow so the flame can be played on the inside surface of the mandrel. Localized overheating must be avoided to prevent distortion of the mandrel.

The blanks are generally heated with a torch that applies heat locally to the area where the tooling force is applied. This technique is shown in Figure 38. Very close control must be maintained to prevent overheating of the parts. The size of the proper torch depends on the thickness of material and the speed and feed rate of the

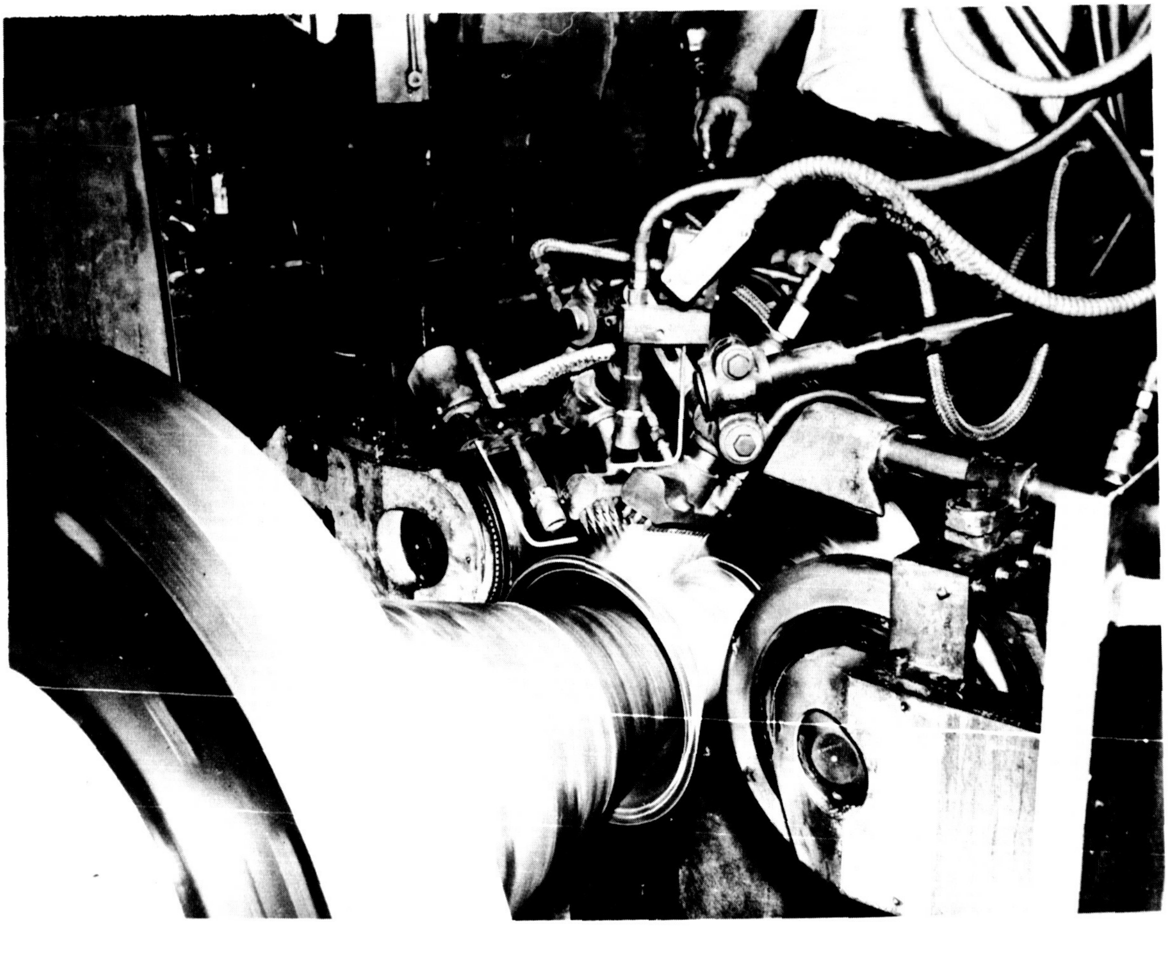


FIGURE 38. TORCH HEATING OF A BLANK DURING CONE-SHEAR FORMING (REF. 55)

operation. Some of the heating methods that can and cannot be used for heating nickel and cobalt alloys because of possible sulfur contamination are given in Table XVII. Blanks for spinning small parts can be heated in a furnace and then transferred to a lathe for spinning. The limitations of this type of operation are determined by the time required for the spinning operation. Shear-forming operations generally take longer and the blanks cool too rapidly to use this technique. Torch heating is the accepted practice for shear-forming operations. The selection of the proper temperature for shear forming is also influenced by the temperature rise associated with deformation at the tool point.

TABLE XVII. SATISFACTORY AND UNSATISFACTORY METHODS OF HEATING NICKEL-BASE AND COBALT-BASE BLANKS (REF. 47)

Satisfactory	Unsatisfactory
Electric	Coal
Acetylene	Coke
Natural gas	High sulfur oil
Butane	Unwashed producer gas
Propane	Unwashed blast-furnace gas
Washed producer gas(a)	Any fuel with sulfur over 0.5 per cent
Washed blast-furnace gas(a)	
Oil with sulfur under 0.5 per cent	

(a) Gas should contain less than 30 grains of total sulfur per 100 ft^3.

Blanks can also be heated by radiation from resistance units located around the part; this technique works well on tubing or preforms. For obvious reasons, this practice is difficult to control when processing flat blanks.

The rollers in shear forming are generally cooled to prevent distortion or creep under high loads. This is usually accomplished by spraying a nonsulfurized lubricant on the roller surface; internal circulating cooling systems are not very practical.

Lubricants. Very little has been published on lubricants specifically for spinning of shear-forming operations. Due to the localized forming forces, the requirements for a lubricant are somewhat more stringent than for other forming operations. In general, the lubricant used should be of a nonsulfurized type to prevent contamination of the metal surface during elevated-temperature forming or subsequent thermal treatments. For room-temperature spinning yellow laundry soap, beeswax, tallow, or mixtures of the latter two are satisfactory. A flash copper plating on the material will reduce tool friction.

Blank Preparation.

Blanks for Spinning. Spinning requires the use of a circular blank with sufficient material to complete the part plus generally some allowance for trimming after forming. The radius for the blank can be determined by examining a section through the completed part and measuring the total length of material required to make the shape starting from the center of the part to one edge. The allowance for trim stock is added to this. The allowance for trimming should be a minimum of 1 inch. The maximum is dictated by the scrap allowed and the swing of the machine.

Blanks for Cone Shear Forming. Cone shear forming requires a blank with a diameter the same as that of the finished part. Some additional allowance for trim stock is desirable to reduce the possibility of cracking in the edge of the part that is likely to occur when shear forming is carried to the end of the blank. The trim allowance should be at least equal to the original blank thickness. A greater allowance is controlled by the amount of trim scrap to be accepted.

Blanks for Tube Shear Forming. Forward tube shear forming requires a blank with an inside diameter equal to the diameter of the finished part. The length of the tube blank is determined by the length of the finished part desired and the reduction to be accomplished. For a part shear formed to a 50 per cent reduction, the length of the blank would be 1/2 of the finished part length. Some allowance for trim should be made in forward shear forming. An allowance of 1 inch for each 10 inches of finished length is normal practice.

Backward tube shear forming requires the same considerations in blank development as forward shear forming. The same reasoning is used in selection of the blank length. The blank inside diameter is the same as the finished tube diameter.

Blank Development. It is sometimes desirable to shear form a configuration other than a cone to a uniform thickness. The proper thickness of the preform can be determined by calculation or by trial-and-error techniques. To calculate the appropriate blank thickness, it is necessary to know the desired finished material thickness, the shape of the part, and the percentage reduction desired. For example, consider the production of the hemispherical part shown in Figure 39 in which a maximum reduction of 50 per cent is expected to produce a constant wall thickness of 0.150 inch. Using the sine law to determine the vertical height of an element in the shell at increments of about 1/2 degree gives a continuous plot of the blank thickness. Since only a 50 per cent reduction is permitted, however, the angle at which this occurs must be determined. In this case 0.150/0.300 = 0.500, which is the sine of 30 degrees; consequently, the edge of the blank cannot exceed 0.300 inch in thickness. Consequently, the edge of the blank must be preformed from the 30-degree intersection to the lip of the hemisphere, as shown in Figure 39.

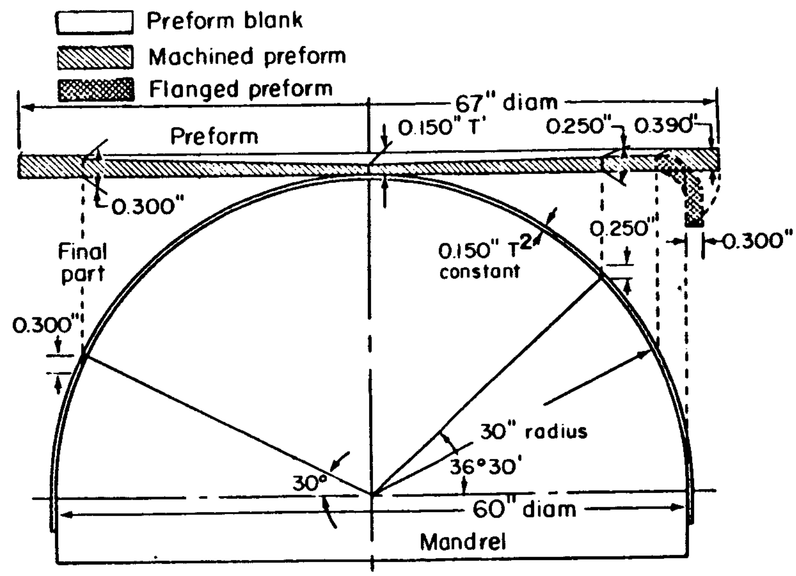


FIGURE 39. TYPICAL DEVELOPMENT OF A BLANK FOR CONSTANT SHEAR-FORMED THICKNESS (REF. 56)

The time involved in calculating the shape of a preform may not be warranted since some deviation from the sine law often occurs.

Trial-and-error methods can be used by the operator to obtain the same results often more accurately. With this approach the operator shear forms a trial blank of constant maximum thickness of 0.300 inch. After forming, the part thickness is measured at various locations and the data are used for correcting the thickness of the next trial blank. This process may have to be repeated several times but the final refinement should give a very accurate part thickness. This technique may be necessary even when the thickness of the blanks is precalculated.

Spinning and Shear-Forming Limits for Nickel and Cobalt Alloys. The information available on spinning of nickel and cobalt alloys is meager, but Wood and associates (Ref. 25) published some studies on the subject. The buckling limits are set by the ratios of the moduli to strengths of the workpiece. Increasing the deformation temperature has little effect on formability up to a temperature of about 1000 F because strength and moduli of nickel or cobalt alloys change at about the same ratio with temperature in this change.

Figure 40 gives some formability limits for manual spinning at room temperature. They are expected to hold for relatively small

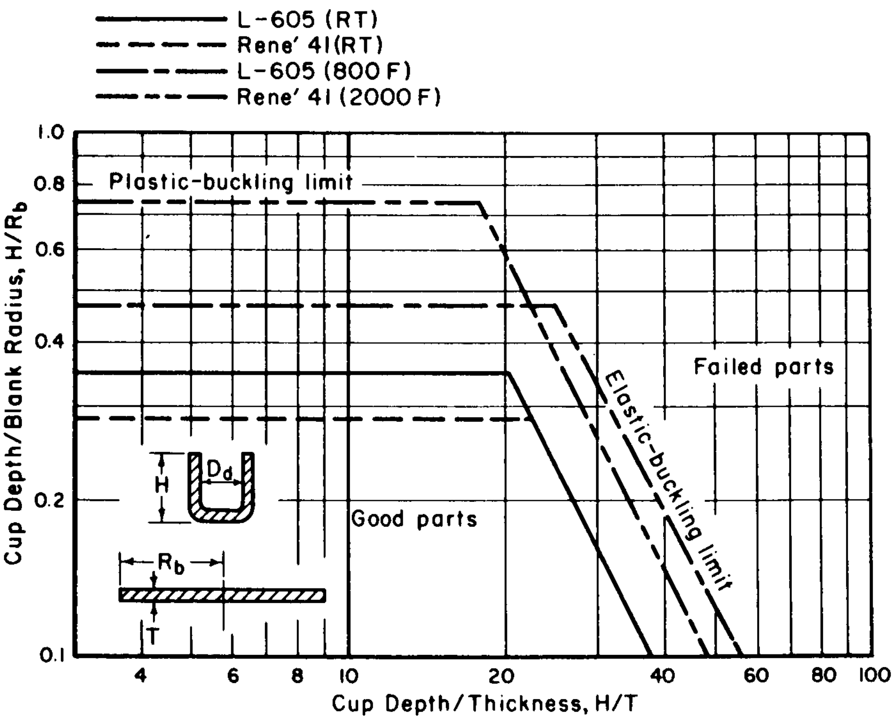


FIGURE 40. SPINNING-LIMIT CURVES FOR L-605 AND RENÉ 41 (REF. 25)

forces and limited amounts of thinning. The data show that spinnability is favored by smaller ratios of blank diameter to sheet thickness. For example, the limit for a 17-1/4-inch diameter, 1/8-inch-thick blank of L-605 alloy appears to be a flat cup 12.25 inches in diameter, 2.5 inches high.

Spinning at elevated temperatures increases the amount of deformation that can be taken before buckling occurs. A higher deformation temperature postpones plastic buckling to higher strains with little effect on the onset of elastic buckling. A higher temperature is necessary to extend the limits for elastic buckling. This analysis indicates that moderately elevated forming temperatures permit spinning cups with larger cup-height to cup-diameter ratios, but does not permit the use of thinner blanks. Comparatively high temperatures are necessary to achieve large ratios of cup height to material thickness. Using the previous example, L-605 could be spun with the same size blank to a flat-cup configuration of 9.75 inches in diameter, 4 inches high at a temperature of 800 F. The blank thickness would need to be increased to 0.625, however, to accomplish this and to prevent failure by elastic buckling.

Spinning of the nickel- and cobalt-base alloys to a deep cup generally requires a number of stages and intermediate anneals. An example of the number of steps required to spin a 4-inch-diameter cup, 4-1/2 inches deep from Nickel 201 is shown in Figure 41. Generally in manual spinning increasing the height of a cup from 1 to 1-1/2 inches constitutes an operation. The material may or may not require an anneal depending on the work-hardening characteristics of the material. As Figure 42 suggests, most nickel-base alloys require annealing after rather small reductions because they work harden rapidly. Most of the nickel-base alloys fall between mild steel and stainless steel in work-hardening characteristics.

The speed at which nickel and cobalt alloys can be spun depends generally on the size of the blank with lower speeds being used on the larger blanks. Speeds 1/4 to 1/2 the speed used to form copper or aluminum give satisfactory results. Spinning lathes with speeds from 250 to 1000 rpm have been satisfactory.

The thickness of material that can be spun manually depends on the pressure that can be applied and the hardness of the material. As the hardness increases, the thickness of material must decrease. Typical material thickness for several alloys are given in Table XVIII.

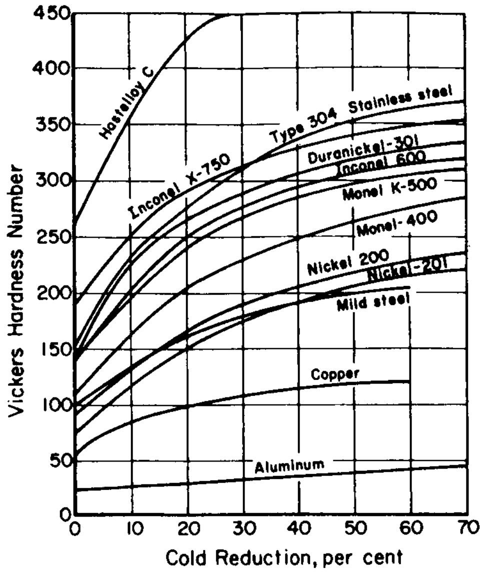


FIGURE 41. STAGES IN SPINNING NICKEL 201 (REF. 47)

Annealed between Stages 2, 3, and 4.

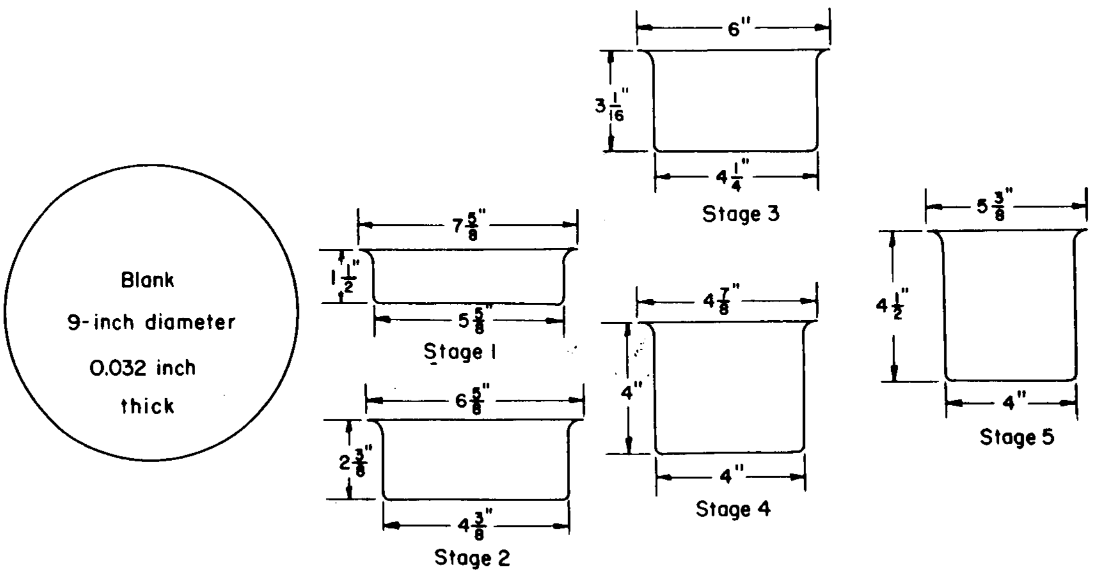


FIGURE 42. INCREASE IN HARDNESS OF VARIOUS METALS AND ALLOYS WITH COLD WORKING (REF. 47)

TABLE XVIII. MAXIMUM BLANK THICKNESS AND MATERIAL HARDNESS FOR MANUAL SPINNING WITH HAND- AND COMPOUND-LEVERAGE TOOLING (REF. 47)

Material	Maximum Hardness, Rockwell B	Maximum Thickness, inch, for Manual Spinning
Nickel 201	55	0.078
Nickel 200	64	0.062
Monel 400	68	0.050
Monel 403	68	0.050
Inconel 600	80	0.037
Inconel 722	94	0.037
Inconel X-750	94	0.037
Nimonic 75	94	0.037

The relative ease of spinning some nickel-base materials is indicated in Table XIX. The ratings are based on fabrication costs; the lower the numerical rating, the greater the difficulty and the higher the cost of spinning (Ref. 57).

Typical tolerances for spun parts are listed in Table XX.

In most spinning operations the part is rotated against a stationary tool. Spinning can also be performed by rotating a tool against a stationary part. An example of this type of spinning is shown in Figure 43 where an Inconel 600 tube is being closed by spinning a hemispherical end. The tube is used for a thermocouple shield. The hardened steel tooling contains the desired design for the end closure so that only one forward movement of the tube against the rotating tool is required to make the part.

Spinning of large parts is demonstrated in Figure 44 where the two bell-mouth ends are spun from Inconel X-750. The parts are approximately 4 feet in diameter.

Shear-Forming Limits. Shear forming is generally used to reduce machining time on parts that require a shape that cannot be made by conventional forming methods. The parts shown in Figures 45 through 50 are representative of parts that can be made of

TABLE XIX. RELATIVE ADAPTABILITY OF NICKEL-BASE MATERIALS TO SPINNING OPERATIONS (REF. 57)

Material	Shallow Spinning[a]	Deep Spinning
Monel, soft temper	1.00	0.85
Inconel	0.90	0.70
"L" Nickel	1.00	1.00
Nickel	1.00	0.92
N-155	0.90	0.50
Hastelloy A	0.75	0.35
Hastelloy B	0.70	0.30
Hastelloy C	0.50	0.10

(a) The material that is best suited to cold spinning has the rating of 1.00. The lower the figure, the higher the cost. The ratings are approximate and will vary with particular circumstances such as size, thickness, and complexity.

TABLE XX. TYPICAL TOLERANCES IN SPUN PARTS (REF. 47)

Nominal Diameter of Part, inch	Minimum Tolerance: Diameter, inch	Length, inch	Cone Cycle, degrees
Under 1.5	±0.010	±0.015	±1
1.5 to 5	±0.015	±0.030	±3
5 to 20	±0.030	±0.030	±3
20 to 36	±0.060	±0.045	±5
36 to 72	±0.120	±0.060	±5

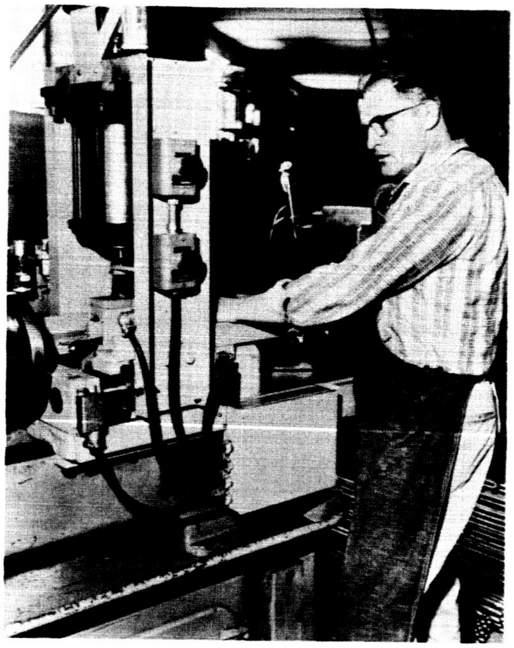


FIGURE 43. SPINNING OF INCONEL 600 USING A ROTATING TOOL AND A STATIONARY PART

Courtesy of Homer L. Hampton, Inc., Willow Grove, Pennsylvania.

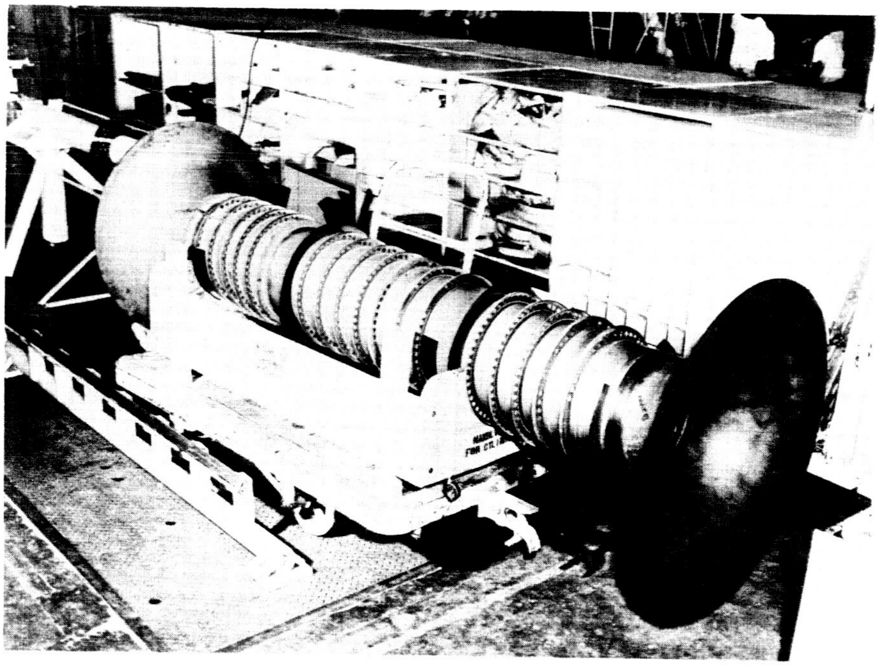


FIGURE 44. SPINNING OF LARGE INCONEL X-750 BELL-MOUTH ENDS FOR USE ON X-15 AIRCRAFT

Courtesy of North American Aviation Inc., Los Angeles, California nickel- and cobalt-base alloys by shear forming. The part may be a simple cone with straight sides, as shown in Figure 45, or one with a complex curvature and a variable wall thickness as shown in Figure 46. Depending on the shape of it and the material, parts are made from flat blanks or from preforms. An example of a shear-forming procedure using a preformed part is shown in Figure 47. In this case the preform was made on a hydraulic press. Spinning or a previous shear-forming operation could also have been used. The economics and flow pattern of material through a given shop will generally determine the procedure to be used.

The wide variety of operations that can be used to make a part are illustrated in Figures 48 and 49. In these samples, a disk and a cylindrical tube were used to form a circular blank and a cylindrical-formed part. They were then trimmed and welded together to make a preform for the final shear-forming operation. The shear-formed part resulting from these operations is shown in Figure 49. Figure 50 shows a shear-formed cone made in one pass at room temperature from 0.063-inch thick R-235 alloy.

Although considerable work has been carried out on shear forming nickel- and cobalt-base alloys, very little specific information has been reported on the process. Some of the available data are given in Table XXI for Inconel X-750, Waspaloy, and René 41 alloys. In general the materials appear to be readily formable by shear forming. Rabensteine (Ref. 58) found that although the nickel-base alloys strain hardened rapidly, they responded well to the shear-forming process. Dimensional accuracies within a tolerance of ±0.002 inch could be maintained when shear forming Inconel 600 at room temperature. Since the elongation of the material in the as-shear-formed condition was very low, the parts required a recrystallizing anneal before they could be used in service.

Properties After Shear Forming. Like other cold-working processes, shear forming increases the strength and reduces the ductility of the workpiece. Table XXII gives information of the kind obtained by Jacobs (Ref. 59) on three superalloys. His tensile tests showed that reductions as light as 20 per cent doubled the yield strengths and increased the ultimate strengths by one-third. Reductions of 30 per cent or more lowered the elongation values to less than 6 per cent, the normal minimum for structural parts. This undesirable effect of cold work can be removed or alleviated by heat treatment. After solution treatment and aging, the deformed materials had good ductility and higher strengths than samples that had not been shear formed. Aging after shear forming developed

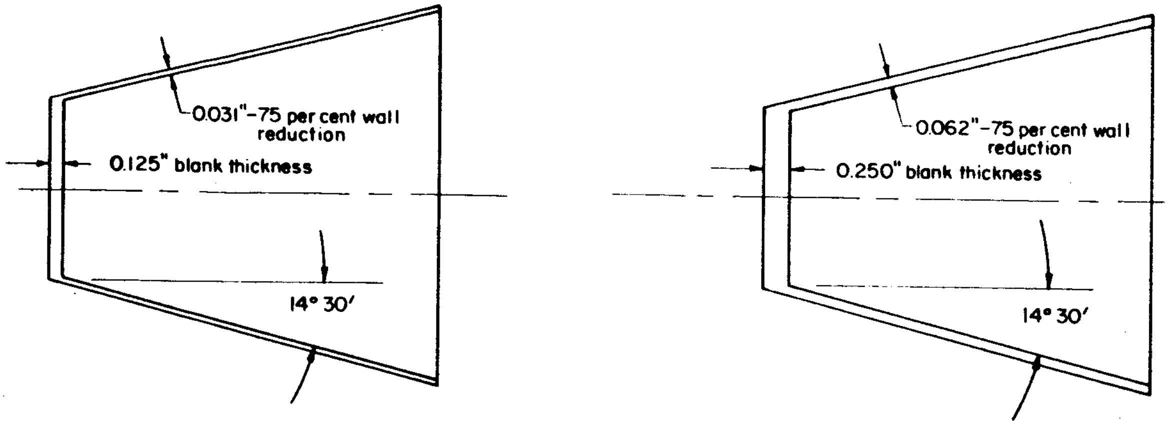


FIGURE 45. CONES SHEAR FORMED FROM AN 8 x 8-INCH-SQUARE STEEL BLANK, 0.050 INCH THICK (REF. 59)

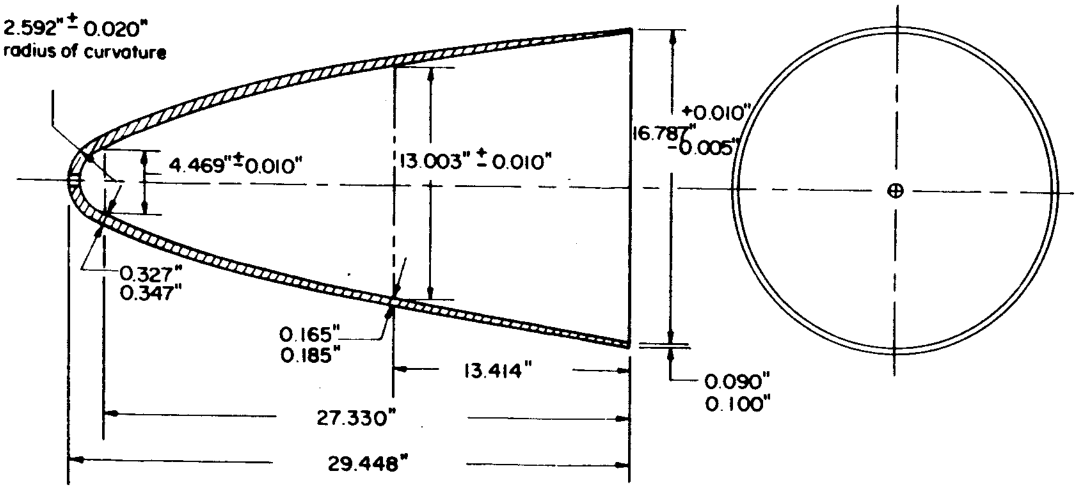


FIGURE 46. SHEAR-FORMED CONE WITH A TAPED WALL MADE FROM A DISHED 7/8-INCH-THICK ALUMINUM BLANK (REF. 59)

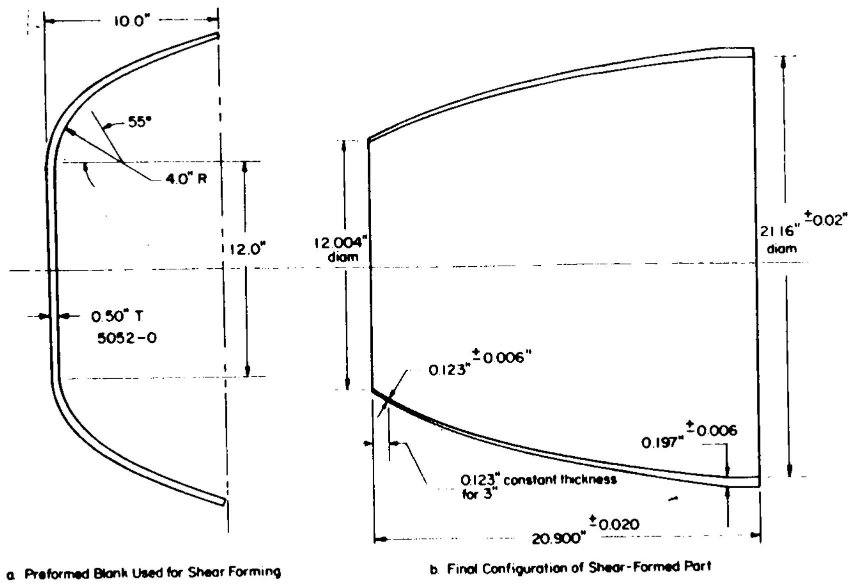


FIGURE 47. SHEAR-FORMED, VARIABLE-WALL CONE MADE FROM A 45-INCH-DIAMETER, 0.50-INCH-THICK ALUMINUM BLANK, PREFORMED TO DISH SHAPE ON A HYDRAULIC PRESS (REF. 59)

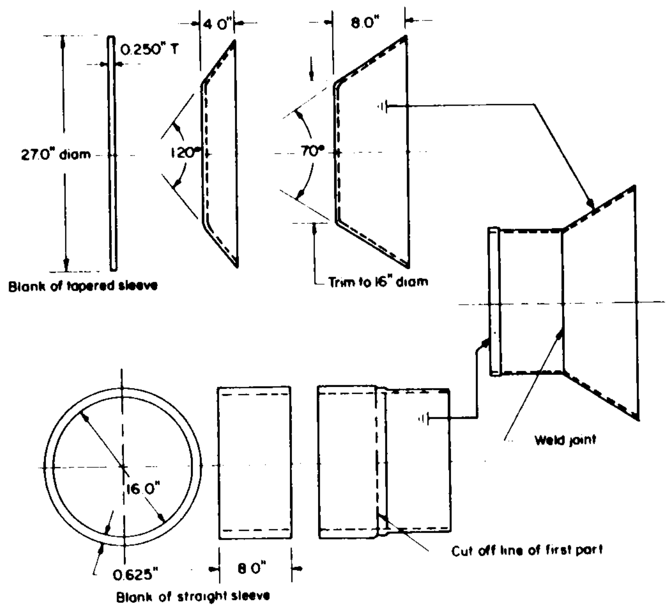


FIGURE 48. SHEAR FORMING OF A CONE AND TUBE MADE OF STEEL FOR A FINAL SHEAR-FORMING OPERATION SHOWN IN FIGURE (REF. 59)

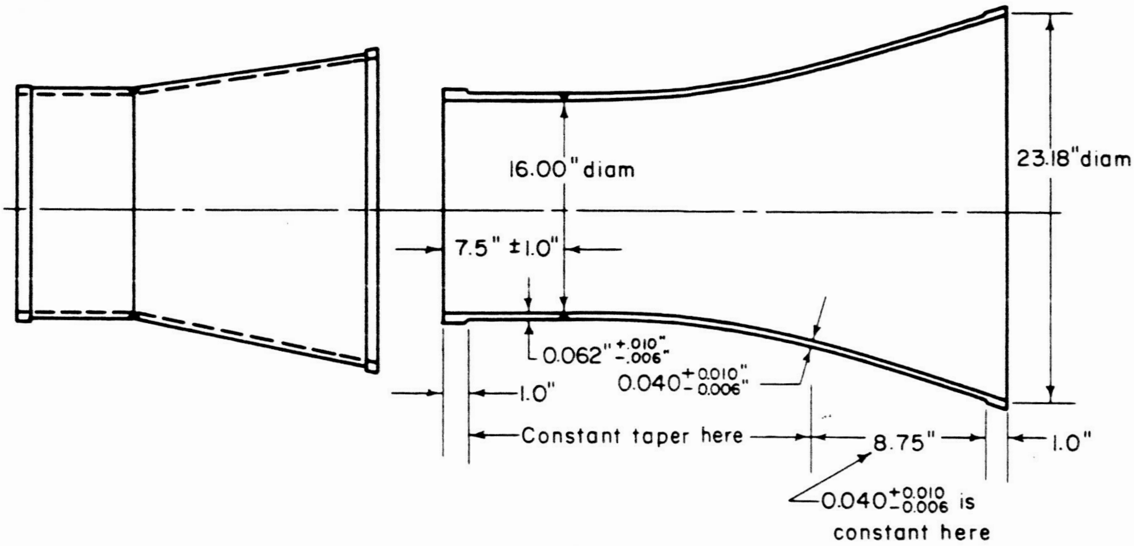


FIGURE 49. SHEAR-FORMED PART MADE FROM TWO SHEAR-FORMED PIECES AND WELDED TOGETHER (REF. 59)

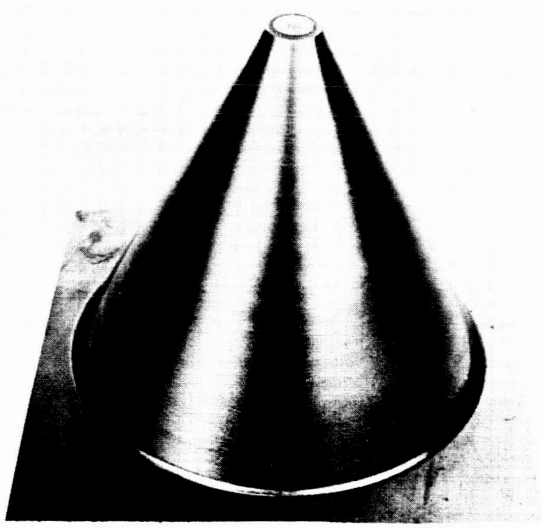


FIGURE 50. R-235 ALLOY SINGLE-ANGLE SHEAR-FORMED CONE (REF. 39)

TABLE XXI. SHEAR-FORMING DATA FOR NICKEL- AND COBALT-BASE ALLOYS

Material and Condition	Preform	Speed	Feed	Roller	Lubrication	Pressure, tons	Per Cent Reduction	Cone: Included Angle, deg	Cone: Smallest, in.	Cone: Largest, in.
				Cone (Ref. 59)						
Inconel X-750 Annealed	12-in. diameter, 0.028 and 0.051 1 inch thick	175 RPM 500 RPM	1.5 in./min 3 in./min	8.7-in. diameter, 0.1 in. radius, 90 in. to work	SAE 40 turbine oil	6	--	60	3	12
M252 Annealed	10-in. diameter	180 RPM 340 RPM	1 in./min 3 in./min	8.7 in. diameter, 0.1 in. radius, 90 in. to work	SAE 40 turbine oil	6	--	60	3	10
				Tube Shear Forming (Ref. 57) (Backward)						
Inconel X-750 Equalized at 1625 F for 4 hours	4-in.-diameter tube 0.100 roll	200 SFM	0.005 in./rev	4-in. diameter 0.075 in. radius	Nebula No. 2 grease	--	45.9-48.2	--	--	--
	0.150	200 SFM	0.005 in./rev	Ditto	Ditto	--	47.9-48.2	--	--	--
	0.150	200 SFM	0.007 in./rev	"	"	--	74.3	--	--	--
	0.150	200 SFM	0.009 in./rev	"	"	--	74.2	--	--	--
	0.150	100 SFM	0.005 in./rev	"	"	--	40.0-46.2	--	--	--
	0.150	150 SFM	0.005 in./rev	"	"	--	40.4-46.3	--	--	--
				(Forward)						
	0.100	200 SFM	0.005 in./rev	"	"	--	39.6-51.1	--	--	--
	0.150	200 SFM	0.005 in./rev	"	"	--	36.0-33.7	--	--	--
	0.200	200 SFM	0.005 in./rev	"	"	--	18.8-30.6	--	--	--
				Cone (Ref. 60)						
	0.208									
Solution treated René 41		215 RPM	2 in./min	14-in. diameter, 3/8 in. radius	Tube Lube B"	--	--	60	--	--
	0.250	150 RPM	10 in./min	14-in. diameter, 3/8 in. radius	Tube Lube B"	--	--	60	--	--

TABLE XXII. RESULTS OF TENSILE TEST ON SHEAR-FORMED MATERIALS (REF. 61)

Material	Condition	Per Cent Reduction	Ultimate Strength(a), 10^3 psi	Yield Strength(a, b), 10^3 psi	Elongation(a), 2-Inch Gage Length, per cent	Hardness(a), Rockwell C
René 41	Solution treated (1975 F)	0	151.3	88.3	44.2	25.1
	As formed	20	196.7	178.2	5.5	43.8
		30	217.3	201.5	5.8	45.6
		40	225.9	208.5	3.8	46.8
		50	254.9	230.0	2.7	49.4
		60	251.6	237.9	2.7	48.7
	Formed and aged	20	226.9	207.7	7.3	48.2
		30	247.9	231.0	5.5	50.2
		40	228.5	188.8	6.8	47.2
		50	237.6	200.4	6.2	49.3
		60	282.3	274.3	1.0	55.7
	Solution treated and aged	0	203.8	144.4	18.8	42.3
	Formed, solution treated, and aged	20	209.8	148.0	16.0	43.8
		30	212.0	158.0	17.0	44.0
		40	212.2	163.0	15.8	44.3
		50	219.6	165.6	15.8	44.4
		60	217.6	157.8	15.2	44.2
Inconel X-750	Annealed	0	111.8	47.9	54.5	B-88.9
	As formed	20	152.5	133.8	9.2	32.9
		30	167.6	156.4	5.7	35.0
		40	179.6	169.4	3.8	37.6
		50	186.8	178.5	2.5	39.9
		60	190.6	186.3	2.7	40.1
		70	200.4	194.6	1.5	41.1
	Formed and aged	20	155.2	114.0	23.8	31.4
		30	163.1	123.7	17.3	33.0
		40	161.5	119.0	17.8	34.8
		50	176.1	129.8	16.7	36.0
		60	230.0	205.4	9.0	46.9
		70	230.4	211.6	7.0	47.2
	Solution treated and aged	0	169.9	111.1	26.7	33.9
	Formed, solution treated, and aged	20	176.3	115.0	26.2	34.3
		30	175.1	114.5	25.7	35.2
		40	177.9	112.3	25.3	34.8
		50	178.7	115.1	24.5	35.0
		60	178.9	114.1	24.5	34.1
		70	181.4	114.9	22.8	34.1
L-605 HS-25	Solution treated	0	135.6	62.0	40.0	B-95.1
	As formed	20	184.8	155.6	11.7	43.6
		30	219.6	191.3	3.0	45.2
		40	234.8	201.4	1.7	47.5
	Formed and aged	20	191.1	178.3	1.8	45.0
		30	226.3	223.9	1.5	49.0
	Solution treated and aged	0	132.3	63.2	65.3	B-94.5
	Formed, solution treated, and aged	20	135.1	60.3	62.2	B-94.5
		30	133.4	60.4	62.8	B-94.5
		40	137.8	68.9	61.5	B-94.8
		50	136.9	64.8	59.8	B-95.4

(a) Average of 3 specimens

Heat-test data

René 41 - solution annealed at 1975 F, water quenched, aged at 1400 F for 16 hours, air cooled

L-605 - solution annealed at 2250 F, water quenched, aged at 1100 F for 16 hours, air cooled

Inconel X-750 - solution annealed at 1950 F, rapid air cooled, aged at 1300 F for 20 hours, air cooled.

All specimens removed from shear-formed cones with the following shape depending on reduction:

Per Cent Reduction	Cone Angle	Base Diameter, inches	Per Cent Reduction	Cone Angle	Base Diameter, inches
20	53°8'	18-1/4	50	30°0'	15-1/4
30	44°27'	18-1/4	60	23°35'	12-1/4
40	26°53'	15-1/4	70	17°27'	12-1/4

(b) 0.2 per cent offset.

reasonably good properties in Inconel X-750 but did not improve the elongation values of the other two alloys appreciably. Rabensteine (Ref. 58) also concluded that the effects of shear forming could be removed by solution annealing and aging. In general, his data indicate that the properties typical of the alloy are restored by such a treatment. Jacobs (Ref. 61) found that recrystallization heat treatments after shear forming usually developed a finer than normal grain size.

DROP-HAMMER FORMING

Introduction. Drop-hammer forming is a progressive deformation process for producing shapes from sheet metal in matched dies with repetitive blows. The process offers advantages for a variety of parts that are difficult or uneconomical to produce by rubber- and contour-forming techniques. Typical applications include beaded panels and curved sections with irregular contours. Drop hammers are often used for details such as half sections of tees or elbows that can be joined together later. The process is best suited to shallow-recessed parts because it is difficult to control wrinkling without a blank holder. Nevertheless, many deeply recessed parts, especially those with sloping walls, are made on drop hammers.

In drop-hammer forming the energy delivered per stroke depends on the mass of the ram and tooling attached to it, and the velocity at which it strikes the workpiece. The striking velocity is controlled by the operator. Since the energy delivered is related to the square of the velocity, very precise control must be exercised by the operator. Relatively large changes in the mass of the moving tool or punch can also have a considerable effect on the hammer operation. The operator must be skilled in judging the effects of changes in punch mass and velocity to insure successful and reproducible results.

Drop-Hammer Presses. The gravity drop hammer is equipped with a weight or ram that is lifted by means of some device such as a rope or a board, and then permitted to drop unrestricted. The pneumatic hammer, shown in Figure 51, and the steam hammer are equipped with a pressure cylinder that lifts the ram and also adds energy to that of the falling ram (Ref. 43). The drop hammer is fundamentally a single-action press. It can be used, however, to perform the work of a press equipped with double-action dies through the use of rubber blankets, beads in the die surfaces, draw-rings, and other auxiliary measures.

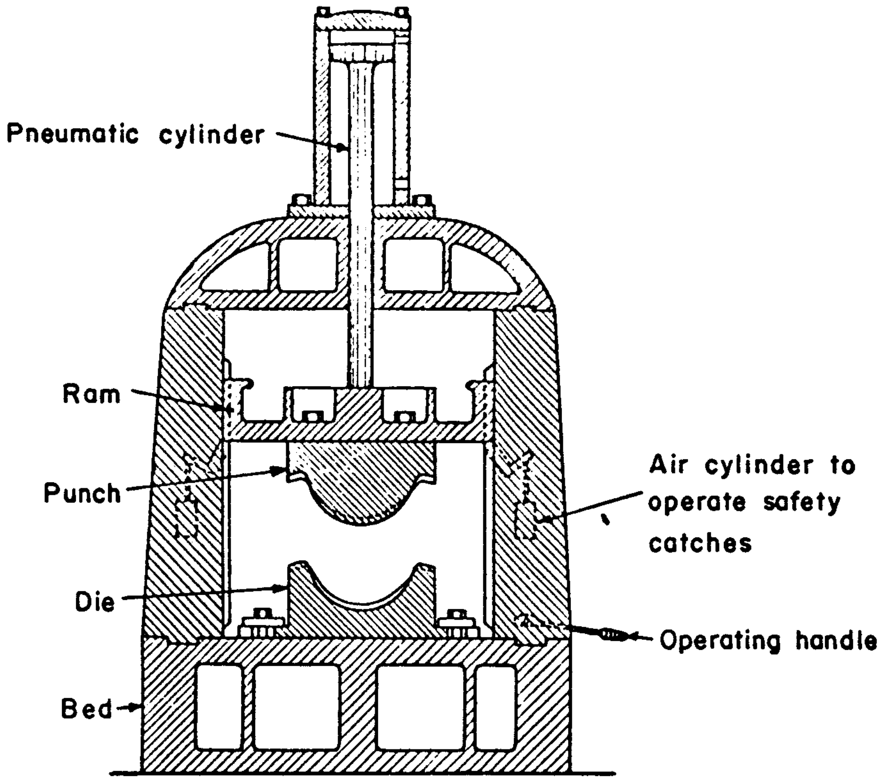


FIGURE 51. SKETCH OF A PNEUMATIC HAMMER (REF. 43)

The platen sizes of commercially available drop hammers vary from 21 by 18 inches to 120 by 96 inches. The smaller machine has a ram weight of 600 pounds and a maximum die weight of 600 pounds, which gives a possible energy level in free fall of 2900 ft-lb. The larger drop hammer has a ram weight of 33,000 pounds and a maximum die weight of 47,000 pounds, which gives a possible energy level in free fall of 90,000 ft-lb (Ref. 62).

Tooling. The basic tool materials for drop-hammer forming are Kirksite, a zinc base alloy, and lead. Lead is preferred for the punches (see Figure 51) since it will deform during service and conform to the female die. The wide use of Kirksite as a die material stems from the ease of casting it close to the final configuration desired. Most companies doing a large amount of drop-hammer work prepare the tooling in their own foundry. Beryllium copper dies have been used for drop-hammer forming, but generally the additional cost is not warranted. Ductile iron and steel dies are used where longer tool life is desired.

Several typical drop-hammer dies are shown in Figure 52 with the finished parts made on them. Sometimes two punches are used:

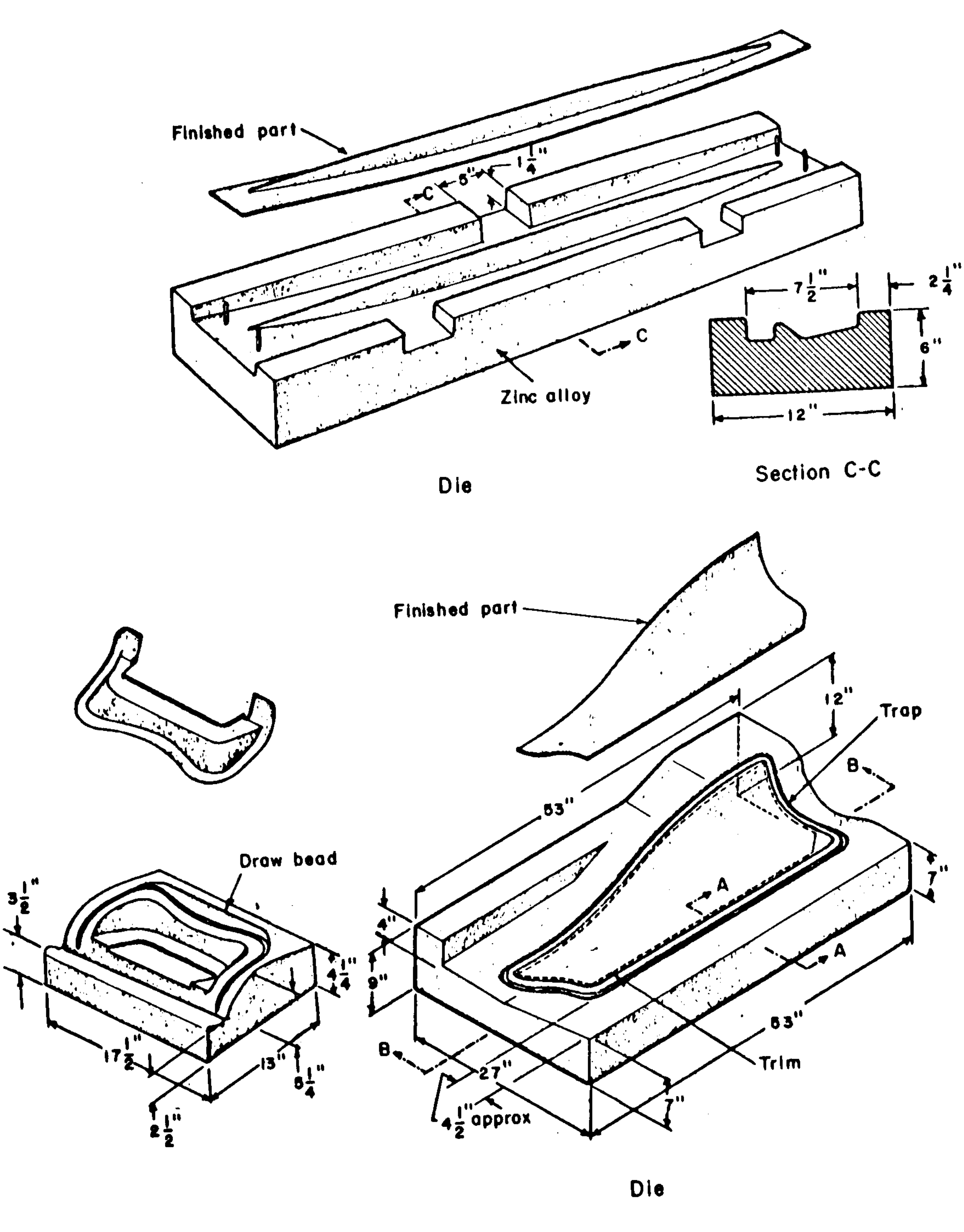


FIGURE 52. TYPICAL DROP-HAMMER DIES AND FORMED PARTS (REF. 43)

a working or roughing punch, and a coining or finishing punch. When the working punch becomes excessively worn, it is replaced by the coining punch, and a new coining punch is prepared. Another method of achieving the same results with one punch is to use rubber pads. Rubber suitable for this purpose should have a Shore Durometer hardness of 80 to 90. Figure 53 indicates the positioning of pads for a particular part. The maximum thickness of rubber is situated where the greatest amount of pressure is to be applied in the initial forming. As the forming progresses, the thickness of rubber is reduced by removing some of the pads after each impact.

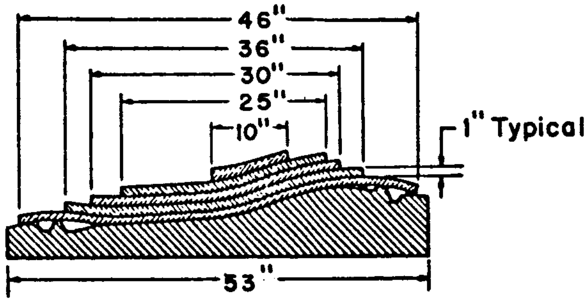


FIGURE 53. POSITIONING OF RUBBER BLANKETS (REF. 43)

The blank would be placed between the die and the first pad.

Smoothly contoured parts can be made in Kirksite dies. Steel inserts should be used in sharply radiused corners of the dies. For complicated parts, cast steel or high-silicon cast-iron dies give better die life.

Mating surfaces of the die set must make contact uniformly. Areas of no contact can cause canning and warping, which are difficult to remove in subsequent forming. Hence, male and female dies should be carefully blued in with allowance for the sheet to be formed.

After a set of tooling has been constructed, the tools are proved out by forming either aluminum or stainless steel parts. Stainless steel is the best trial material since it has springback characteristics similar to the nickel- and cobalt-base alloys.

Buckling is difficult to control in drop-hammer forming because hold-down rings are not normally used. To minimize buckling, most of the deformation should result from stretching rather than shrinking. When shrinking is necessary, as in producing deeply recessed parts, a draw bead (Figure 52) will help to prevent buckling. The draw bead becomes effective only near the end of the stroke. Parts made in dies with draw beads require more material because the beaded sections have to be removed by trimming.

When parts cannot be readily formed with one blow in one die set, better results can sometimes be obtained by introducing two-stage tools, each of which permits one-blow forming, rather than using multiple blows in one set of tools. In such cases, good results can be obtained by making the part slightly oversize in the first-stage tools and by coining the final shape in a second set of tools.

Techniques of Drop-Hammer Forming. The procedures for forming nickel and cobalt alloys at room temperature in drop hammers resemble those used for stainless steel. The process offers the advantages of flexibility, low die costs, and short delay times between design and production. A number of individual forming operations can be combined on the drop hammer such as: drawing, beading, joggling, and bending. Two parts that incorporate these shapes are shown in Figure 54. There are some limits to the process that should be observed for satisfactory production. The minimum draft angle should be at least 3 degrees. This minimum draft angle should be used only for the wall adjacent to the part outline where sufficient material is available for the draw. The bend radii should be as large as possible. Undercuts should be avoided, and transitions should be made as gradual as possible. Internal contours or recesses may be formed by stretching alone. Hemispherical

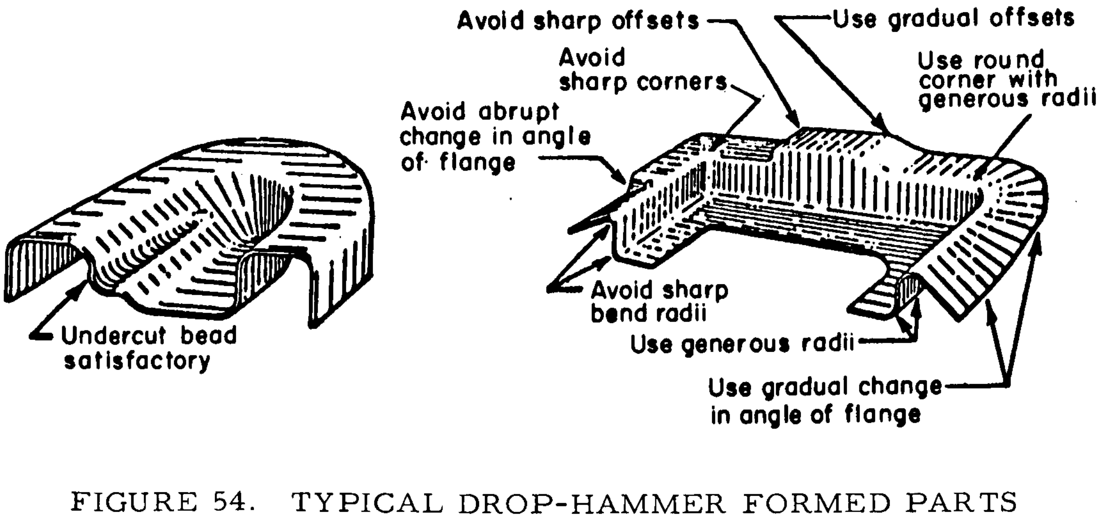
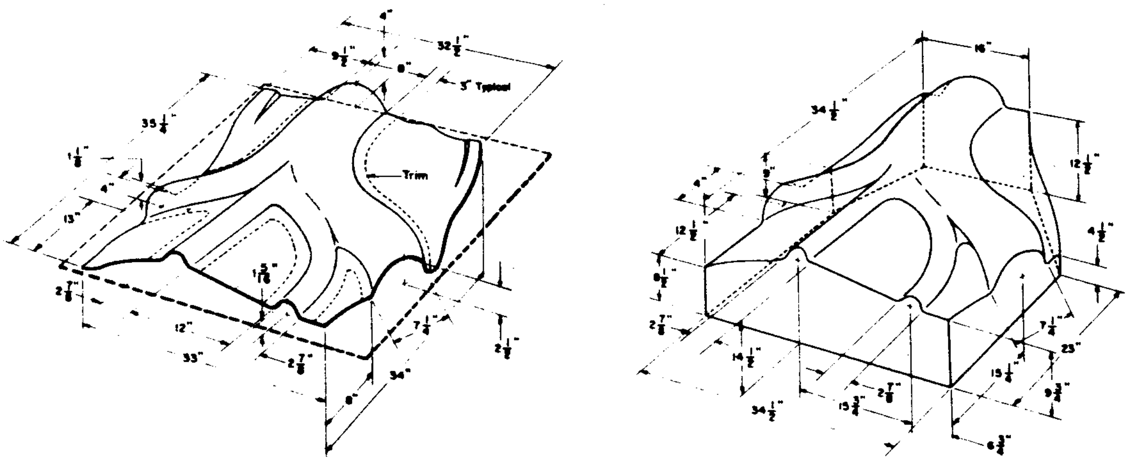


FIGURE 54. TYPICAL DROP-HAMMER FORMED PARTS

Courtesy of Boeing Airplane Company.

indentations can be designed into the tooling in trim areas adjacent to stretched recesses to absorb excess material and to prevent wrinkling. Considerable hand work and expense may be saved by allowing some wrinkling in noncritical areas. Regions where wrinkles are not objectionable should be marked on the drawings.

Drop hammers are often used for forming semitubular parts of complex design. Two halves formed in this manner are then welded to form a complete tubing assembly. In forming a semitubular part with a number of branches, the major limiting design factor is the radius, within the hold-down surface, at the apex of a fork, between two branches meeting at an acute angle. The radius at this point should not be smaller than one half of the depth of the draw. A complex semitubular part and die for drop-hammer forming is shown in Figure 55. The starting blank size and the trim areas of the part after forming are indicated. This particular part required several stages for forming and was made from stainless steel.



a. Formed Part Before Trimming

b. Punch

FIGURE 55. DROP-HAMMER FORMING OF SEMITUBULAR PART MADE FROM 301 STAINLESS STEEL (REF. 43)

Lubricants used in drop-hammer forming of nickel and cobalt alloys should be of the nonsulfurized types if the material is to receive a subsequent thermal treatment. Extreme pressure oils and pigmented drawing compounds are preferred. Some of the specific lubricants that have been used in deep drawing of nickel and cobalt alloys, such as beef tallow and castor oil, also should be usable in drop-hammer forming. The lubricants are generally swabbed onto the blank surface prior to forming. The lubricants should be removed from the part surface after the parts are formed. Complete removal is necessary before any subsequent thermal treatment.

Blank Preparation. The blanks for drop-hammer forming are generally rectangular in shape and are prepared by shearing. The blank should be large enough to yield a part with a 2 to 3-inch-wide flange in order to facilitate drawing of the metal during forming. Where multistage forming is used the part may be trimmed so that only a 1/2-inch-wide flange is left for the final forming stage.

Sheared edges are generally satisfactory for drop-hammer forming since the wide flange permits some cracking in the area without harming the part. The blank should, however, be deburred to reduce possible damage to the tooling.

Forming Limits. The severity of permissible deformations in drop-hammer forming is limited by both the geometrical considerations and the properties of the workpiece material. According to Wood (Ref. 25) the forming limits can be predicted by considering parts of interest as variations of beaded panels. For parts characterized in this way, the critical geometrical factors are the bead radius, R, the spacing between beads, L, and the thickness of the workpiece material, T. These parameters are illustrated in Figure 56.

The upper and lower forming limits depend entirely on geometry and are the same for all materials. The ratio of the bead radius, R, to bead spacing, L, must lie between 0.35 and 0.06. The lower formability limit is controlled by the necessity for producing uniform stretching and avoiding excessive springback. If the R/L ratio is too small there will be a greater tendency for localized stretching at the nose of the punch. Furthermore, the material may deform elastically, not plastically, and springback will be complete when the load is removed.

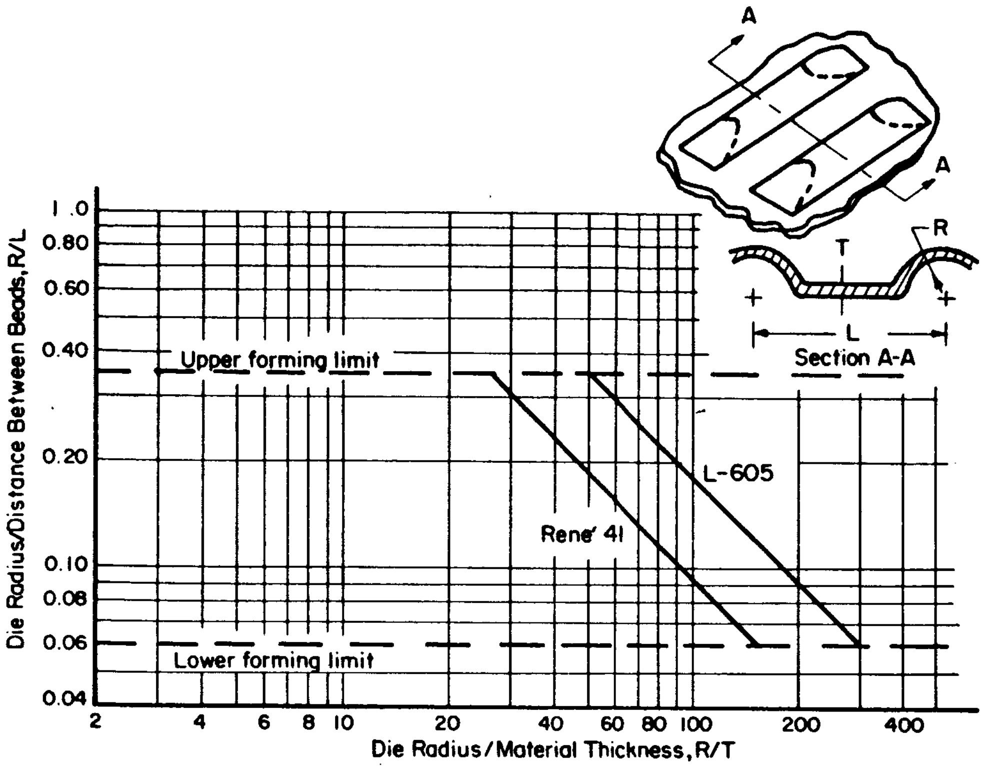


FIGURE 56. DROP-HAMMER-FORMING-LIMIT CURVES FOR RENÉ 41 AND L-605 IN THE SOLUTION TREATED CONDITIONS AT ROOM TEMPERATURE (REF. 25)

Within the limits set for all materials by the R/L ratio, success or failure in forming beaded panels depends on the ratio of the bead radius to the sheet thickness, R/T, and on the ductility of the work-piece material. The part will split if the necessary amount of stretching exceeds the ductility available in the material. The splitting limit can be predicted from the elongation value, in a 0.5-inch gage length, in tensile tests at the temperature of interest. The general relationship is (Ref. 25):

$$\frac{R}{L} = \frac{50\,(e_{0.5})^2}{(R/T)}, \qquad (20)$$

where

R = bead radius

L = center to center spacing of beads

$e_{0.5}$ = engineering strain for a 0.5-inch gage length

T = thickness of the blank.

The equation indicates that the permissible R/L ratio decreases as the R/T value increases.

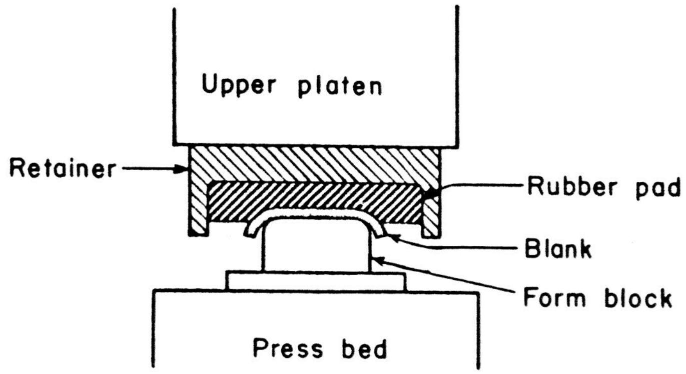
Formability limits constructed in this way for René 41 and L-605 alloys in the solution-treated condition are shown in Figure 56. Although the limits apply to beaded panels they can be used with caution as guides to forming other types of parts with drop hammers.

The minimum thickness for hammer-formed parts of nickel and cobalt alloys is about 0.025 inch. A reduction in uniform elongation with material thicknesses below this result in reduced formability. Heavier stock should be used for more complex shapes.

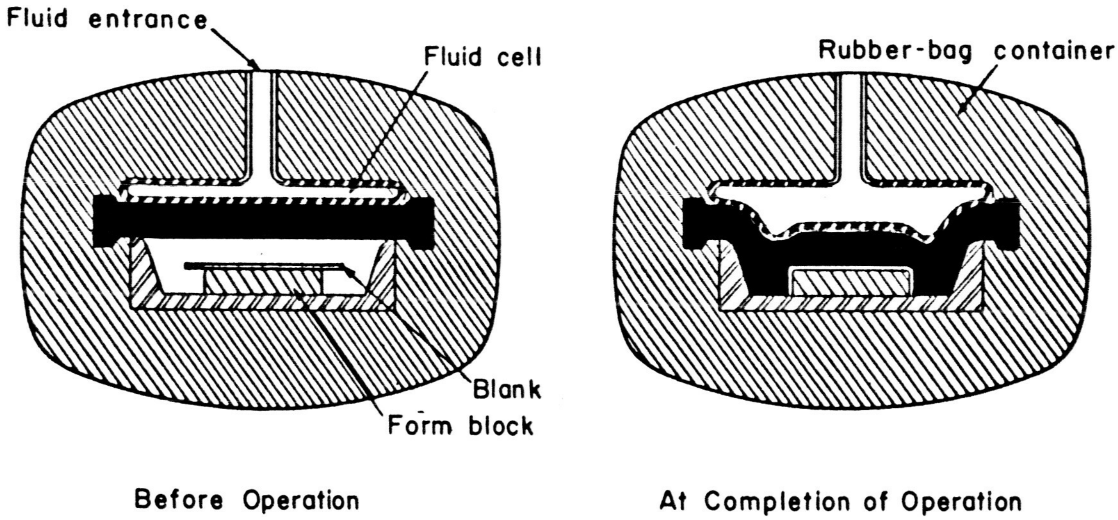
It is difficult to predict proper springback allowances for complex parts. Forming the material in the solution-treated or annealed condition minimizes springback so that dies made to net dimensions will generally produce parts to forming tolerances of 1/16 inch.

TRAPPED-RUBBER FORMING

Introduction. In trapped-rubber forming, a rubber pad is used as part of the tooling, usually as the female die for a punch or group of punches. The rubber pad is confined or trapped in a retainer as indicated in Figure 57. Relative motion of the upper and lower platens causes the rubber to fill the space between the retainer and the part and forces the workpiece to assume the shape of the punch. Among other advantages, trapped-rubber forming requires only the punch, which is the simpler half of conventional tooling. The process is best suited to making small lots of parts with shallow recesses. The original or Guerin approach to trapped-rubber forming and a modification by Wheelon are shown in Figure 57. In the latter process, inflating a rubber bag with a pressurized fluid causes the rubber pad to deform the blank and form the part. Either process can be used to form several parts simultaneously depending on their size and the area of the press available for mounting punches.



a. Guerin Process



b. Wheelon Process

FIGURE 57. METHODS USED FOR TRAPPED-RUBBER FORMING (REFS. 43, 63)

The maximum pressure ordinarily developed in trapped-rubber forming is about 10,000 psi. Impact presses are able to produce higher pressures. Parts formed by this process generally require some additional work to correct for springback. The process is usually conducted at room temperature.

The trapped-rubber process has been used extensively in the aircraft industry for forming parts with straight and curved flanges. The parts may be formed in one operation or in stages requiring several form blocks depending on the shape of the part. Some typical trapped-rubber formed Inconel X-750 aircraft parts are shown in Figure 58. These were made from 0.025-inch-thick material in the solution-treated condition.

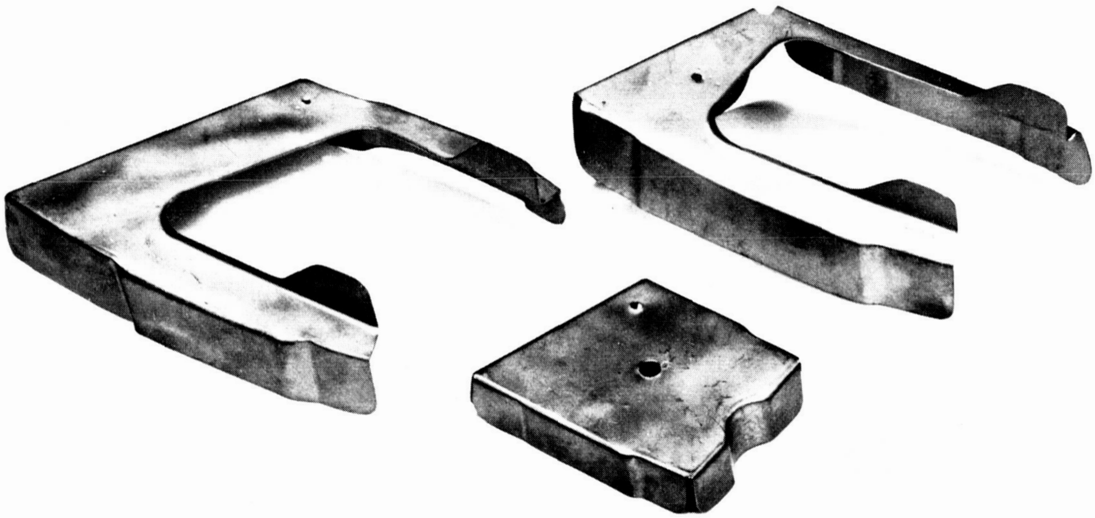


FIGURE 58. INCONEL X-750 PARTS, 0.025-INCH THICKNESS GAGES, TRAPPED RUBBER FORMED (REF. 29)

Aged at 1300 F for 20 hours.

Parts shown approximately 1/4 size.

Trapped-Rubber Presses. Trapped-rubber presses may be of the single- or double-action type. Generally, the smaller presses are single action while the larger presses are of the double-action type. Most of the standard single-action hydraulic presses can be equipped with a trapped-rubber head for forming operations. A small trapped-rubber press might have a loading capacity of 500 tons and a working area of 500 square inches. One of the larger presses, shown in Figure 59, has a load capacity of 7000 tons and a working area of 2200 square inches. The limitations on equipment are generally set by the maximum pressure that can be generated in the rubber and the strength of the container surrounding the rubber pad.

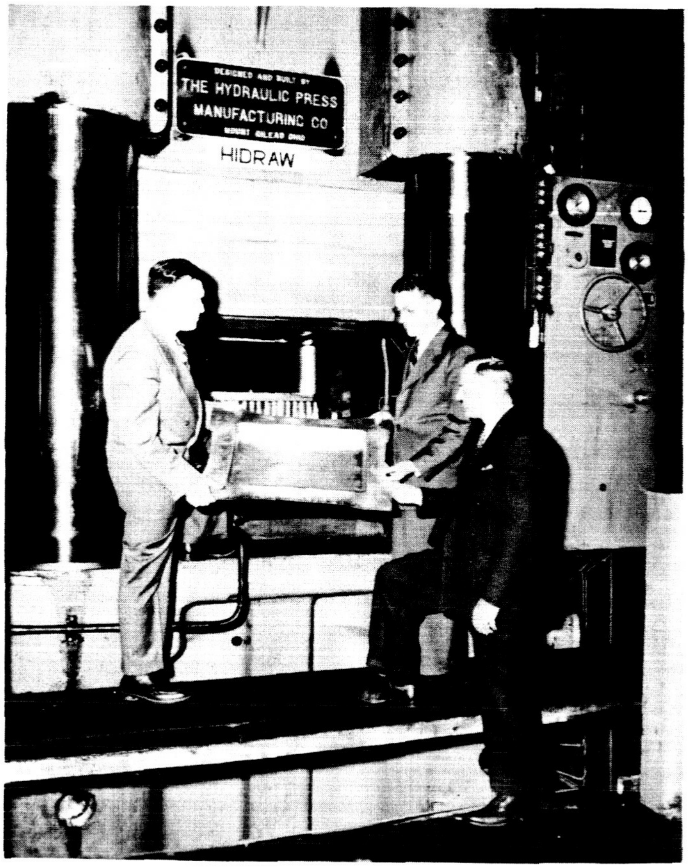


FIGURE 59. 7000-TON TRAPPED-RUBBER PRESS

Courtesy of H. P. M. Corporation.

New developments in trapped-rubber forming are centered around methods of increasing the pressure that can be applied to the rubber. Heavier containers are being built; new synthetic-rubber compositions, which will withstand the higher pressures, are being developed. A partial list of available press equipment and sizes are given in Table XXIII. For specific requirements, the manufacturers should be contacted.

TABLE XXIII. SIZES OF TYPICAL TRAPPED-RUBBER PRESSES

Manufacturer	Work Area, sq in.	Press Stroke, inches	Forming Pressure, psi	Strokes/Hr
Cincinnati Milling Machine Co.	50	5	5,000	1200
	113	7	10,000	1200
	177	7-9	Up to 15,000	1200
	314	10	Up to 15,000	1200
	490	12	10,000	1200
	531	12	Up to 15,000	90
	804	12	10,000	90
H.P.M. Corporation	Up to 2200	15	Up to 7,000	20

Tooling. The tooling for trapped-rubber forming can be made from a variety of materials depending on the tool life desired and the operating conditions. For room-temperature forming, cold-rolled steel is often used because it is a low-cost material and is fairly easy to machine. Where longer tool life is required, hardened carbon steel or alloy tool steel is used. Where the part shape is more complex and the punch is more difficult to machine, cast iron and ductile iron have been used. Kirksite has been used, but may give a very short life in working nickel- and cobalt-alloy materials.

Since there is very little rubbing action on the die during forming, very little wear is expected in normal operation. Most of the wear can be attributed to the methods used for removing formed parts from the tools. The pressure exerted by the flexible pad is fairly uniform over the part and die. Any imperfections in the die will be reproduced on the part if the pressure is sufficiently high. This is more troublesome with softer workpiece materials like aluminum than it is with nickel or cobalt alloys. A good surface finish should be maintained on the die to permit easy movement of the blank as the metal is drawn in, and to prevent scratching or marring of the surface during forming.

Sometimes a pressure plate is used over the punch to assist in keeping the surface of the part flat. The surface plate should also have a good finish and be aligned on the punch by means of tooling pins. Pins also serve to keep the blank in proper position on the punch during forming.

Normally, the tooling is made to net dimensions and the springback in the part removed by benching or subsequent forming operations. Sometimes, springback can be minimized on flanges by undercutting the angles by the amount of springback expected. This technique is not very successful when the flange angle is 90 degrees or more. Another technique that can be used to extend forming limits is to place bars of lead over the flange area. Additional pads of rubber may also be placed over those areas where more pressure is required.

Techniques of Trapped-Rubber Forming. The multidirectional pressure in trapped-rubber forming, as compared to unilateral pressure in conventional drawing, results in more uniform stresses in the blank. This permits greater draws and drawing of less uniform shapes with sharply changing contours than with conventional dies. In trapped-rubber forming, the die radius is variable and depends on the pressure applied. As the forming pressure is increased, the radius of the part is decreased until the radius on the tool is reached. The forming pressure can be adjusted during the forming operation with the trapped-rubber process. In practice, the pressure is maintained at a low level until the material has been stretched to the deepest part of the die and then the pressure is increased until the desired radii have been obtained on the part.

With trapped-rubber forming, there is no transmission of stress through the wall of the partially formed part. The material is supported across the die by uniform pressures while the material is unsupported at the forming radius. Since small increments of the blank are stretched into the void and against the punch at one time, there is no thinning of the partially formed section of the part. By proper adjustment of the forming pressure and the speed, the stretching and thinning of the metal during forming can be made to compensate for the increase in flange thickness resulting in a part with fairly uniform wall thickness. Near the completion of the forming stroke, the pressure must be increased to prevent wrinkling of the flange. The reduced gripping area, increased thickening, and work hardening requires an increase in pressure to complete the forming.

The use of an external flange on trapped-rubber parts provides restraint and assists in obtaining closer dimensional tolerances. The extra material can be removed after forming. When blanks are trimmed to final size before forming, lead strips are often used as a substitute for the flange to assist in forming since the lead acts like a mating die.

Lubricants are seldom used in trapped-rubber forming since there is very little siding-type friction involved in the process. If a lubricant is used, the nonsulfurized types should be used when the parts are to receive a subsequent elevated-temperature treatment.

Blank Preparation for Trapped-Rubber Forming. Blank preparation for trapped-rubber forming is the same as for other forming processes. This process, however, generally necessitates the use of tooling holes for maintaining part location on the punch during forming. They must be located accurately within 1/32 inch or difficulty will be experienced in loading the blanks and, possibly, from elongation of the holes during forming. The tooling holes should be deburred the same as with the rest of the blank.

Nickel- and Cobalt-Alloy Trapped-Rubber-Forming Limits. The trapped-rubber process is commonly used for producing contoured flanged sections and stiffened panels from nickel and cobalt alloys. Finished parts can be made if the requirements for the bead radius, flange height, bead spacing, or the free-forming radius are not too severe. If the design requirements exceed the capabilities of the material, the process may be used to fabricate preforms that are subsequently formed to final size after solution annealing.

Ductility and stiffness are the principal properties influencing the performance of a material in trapped-rubber forming. Wood and associates (Ref. 33) have shown the quantitative relationships between mechanical properties determined in tensile and compressive tests and formability limits. The conventional values for tensile elongation correlate with the maximum permissible amount of stretching without splitting. In stretch flanging, splitting limits are given by the maximum ratio of the flange height to the contour radius. Generally speaking, the contour radius on the forming block for nickel- and cobalt-alloy parts should be 5 inches or larger for sheet thicknesses up to 0.080 inch. Buckling, which depends on the ratio of the elastic modulus to the yield strength of the material, affects the maximum height to which flanges can be formed. The tendency for buckling increases with the ratio of the flange height to the thickness of the workpiece material. In shrink flanging, using higher forming pressures minimizes buckling or wrinkling. That expedient is not helpful in stretch flanging. The minimum permissible bend radii in rubber-pad forming of various nickel and cobalt alloys are the same as those given in the section on brake forming. Higher forming pressures are needed to produce smaller bend radii.

For tight bends, the minimum practical flange length increases with sheet thickness. For forming pressures of 5000 psi or more, the ratio of flange length to sheet thickness should fall in the range from 25 to 30. Flange angles can usually be formed to tolerances of about 5 degrees.

Some parts made by the trapped-rubber process include beads, shrink flanges, and stretch flanges. If so, failures may occur in various regions depending on the severity of the shape change required at those locations. Therefore, it is convenient to consider, separately, the different criteria limiting formability.

Figures 60 and 61 show the geometrical limits for stretch and shrink flanges that can be produced from René 41 and L-605 by the trapped-rubber process at room temperature. They are based on a theoretical analysis of the mechanics of the operation and knowledge of the tensile properties (Ref. 33). Experiments at room temperature by the same investigators indicate the formability limits are realistic. Although the limits for various part shapes appear to be close together, the differences are sometimes important. For instance, when the stretch-form-block radius is 10 inches, the splitting limits indicate that the maximum thicknesses for René 41 and L-605 are 0.280 and 0.300 inch, respectively. The corresponding flange heights for those thicknesses would be 0.70 and 0.90 inch maximum.

From the standpoint of buckling in compression flange forming, the L-605 alloy has the better formability. For equal flange heights and sheet thicknesses, it can be formed to a smaller contour radius. After constructing the formability boundaries analytically from mechanical-property data, Wood and associates (Ref. 33) verified them experimentally.

Table XXIV describes conditions found to be satisfactory for trapped-rubber forming in other investigations. Inconel 718 was found to have springback on both the shrink and stretch flanges between 0 and 4 degrees (Ref. 62). The springback was minimized by the use of an impact rubber press and by the use of 1/2-inch-thick lead overlays. The springback could be subsequently removed by benching on the forming dies.

Wilcox's (Ref. 40) tests indicated that parts made of René 41, 0.025 inch thick, required excessive benching time to remove distortion and that hand work was inadequate for thicker materials. Rubber pressures of 3900 and 11,100 psi on a hydraulic press as well as impact pressures from a trapped-rubber-head-equipped drop hammer were used in his work.

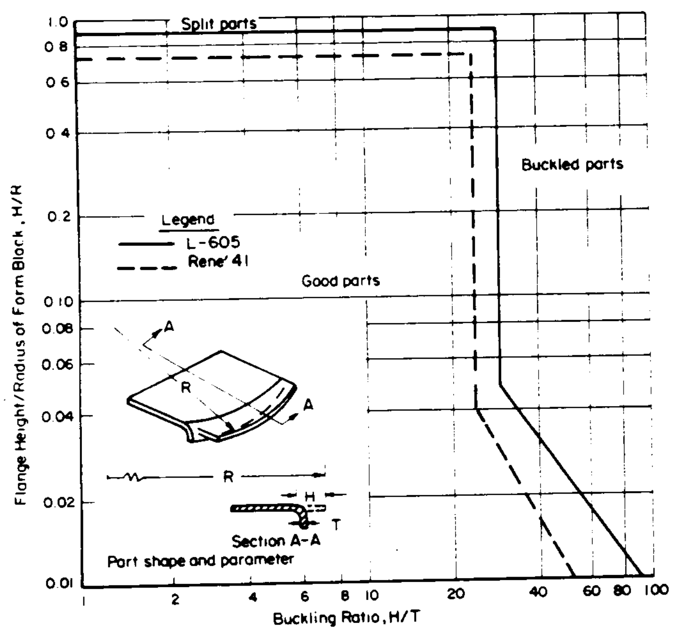


FIGURE 60. CALCULATED FORMABILITY LIMITS OF SOLUTION-ANNEALED RENÉ 41 AND L-605 ALLOYS IN RUBBER-STRETCH-FLANGE FORMING AT ROOM TEMPERATURE (REF. 33)

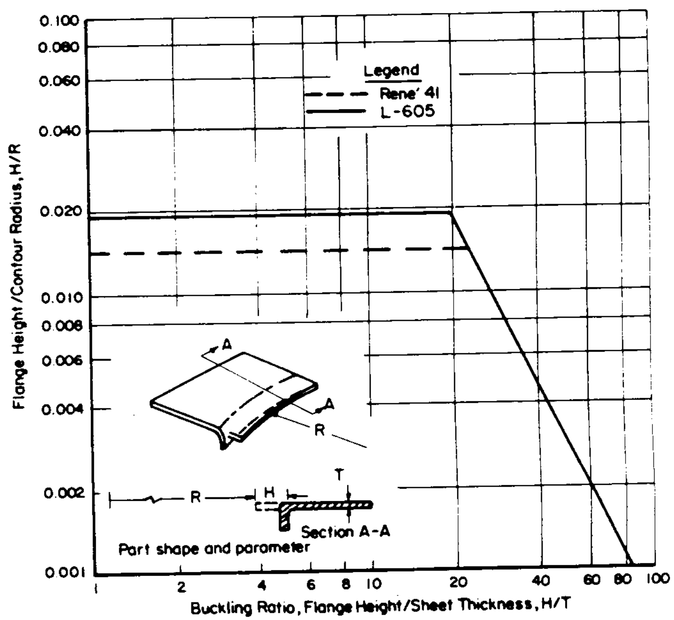


FIGURE 61. CALCULATED FORMABILITY LIMITS OF SOLUTION-ANNEALED RENÉ 41 AND L-605 ALLOYS IN RUBBER-COMPRESSION-FLANGE FORMING AT ROOM TEMPERATURE (REF. 33)

TABLE XXIV. STRETCH FLANGING BY THE TRAPPED-RUBBER PROCESS

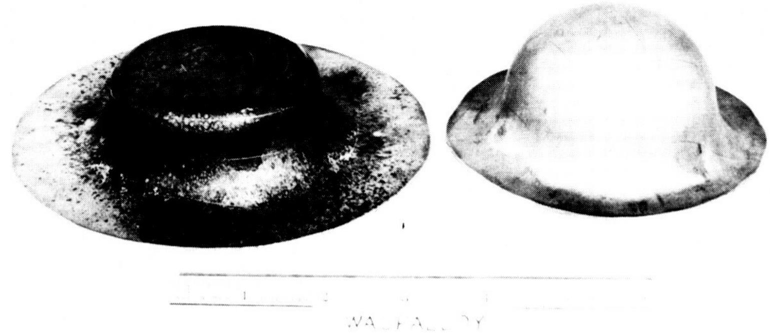
Material and Condition	Thickness, inch	Die Radius, inches	Bend-Radius Thickness Ratio, T	Flange Angle, degrees	Flange Height, inches	Stretch, per cent	Reference
Inconel X-750	0.025	6	1	90	0.125-1.750	2.1-41.2	29
Annealed	0.040	5	1	90	0.125-1.375	2.6-37.9	
	0.062	4	1	90	0.125-1.125	3.2-39.5	
	0.093	3	1	90	0.125-0.750	4.3-33.3	
René 41	0.025	6.05 (stretch)	2	90	1.30-1.40		40
		9.93 (shrink)	2	90	0.86-0.96		
	0.063	6.05 (stretch)	2	90	1.40-1.60		
		9.93 (shrink)	2	90	0.86-1.16		
Inconel 718	0.048	6.05 (stretch)	2	90	1.40-1.60		62
		9.95 (shrink)	2	90	0.86-1.06		

Germann and Shaver (Ref. 29) showed that Inconel X-750 could be formed to greater percentages of shrink and stretch by using an intermediate anneal. They found that a forming pressure of 1000 psi was adequate for forming 0.025 to 0.093-inch-thick material. The amount of springback in the flanges was not reported, but it was indicated that the test results were verified in the production of aircraft trapped-rubber parts.

Some examples of parts formed by the trapped-rubber process are shown in Figures 62 through 66. The cup and hemisphere shown in Figure 62 were formed from 0.063-inch-thick Waspaloy in the solution-annealed condition. Attempts to increase the depth of draw resulted in wrinkling, as shown in Figure 63, for the same material. Hastelloy R-235 was formed on the same tooling and resulted in the cups shown in Figure 64 and the hemispheres shown in Figure 65. The R-235 alloy has slightly better formability than Waspaloy.

Impact rubber forming was used to fabricate the tube-elbow half shown in Figure 66. The R-235 alloy was 0.063 inch thick and was formed in the solution-treated condition.

Beading is another common application for rubber forming. The bead radius is important because the stiffening effect decreases as the radius increases. The minimum radius that can be formed in a nickel- or cobalt-alloy sheet is the same as that for brake bending. How closely the minimum bend radius of either a bead or the die-bend radius of the forming block can be approached depends on the forming



Waspaloy

FIGURE 62. WASPALOY TRAPPED-RUBBER-FORMED CUP AND HEMISPHERE (REF. 37)

Waspaloy

FIGURE 63. WASPALOY TRAPPED-RUBBER-FORMED CUP (REF. 37)

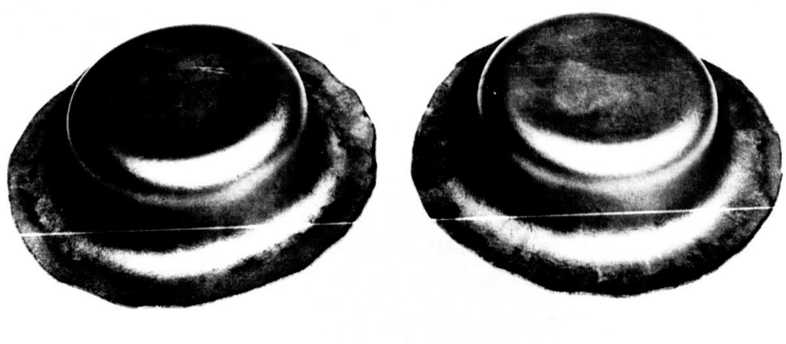


FIGURE 64. R-235 TRAPPED-RUBBER-FORMED CUPS (REF. 39)

FIGURE 65. R-235 TRAPPED-RUBBER-FORMED HEMISPHERES (REF. 39)

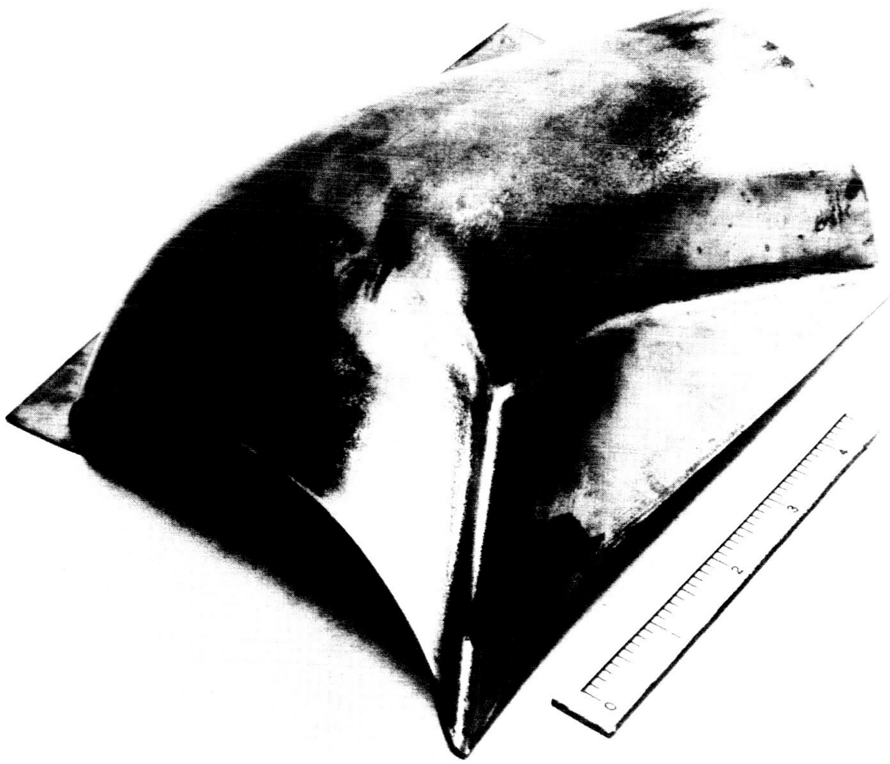


FIGURE 66. R-235 TRAPPED-RUBBER-FORMED HEMISPHERE (REF. 39)

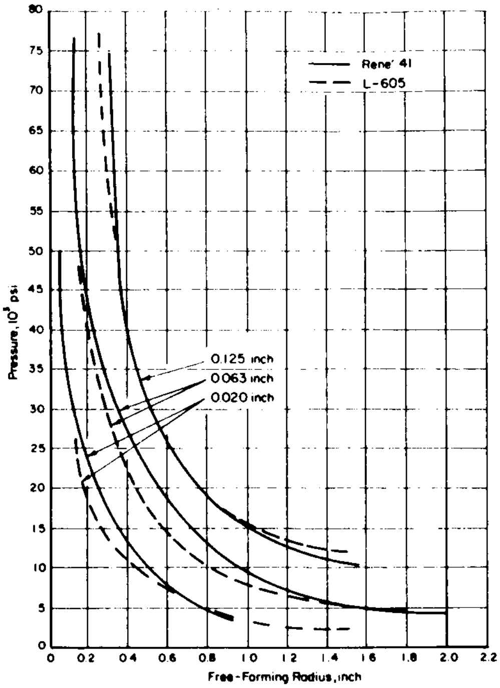


FIGURE 67. EFFECT OF PRESSURE ON FREE-FORMING RADIUS FOR RENÉ 41 AND L-605 IN THE SOLUTION-TREATED CONDITION (REF. 27)

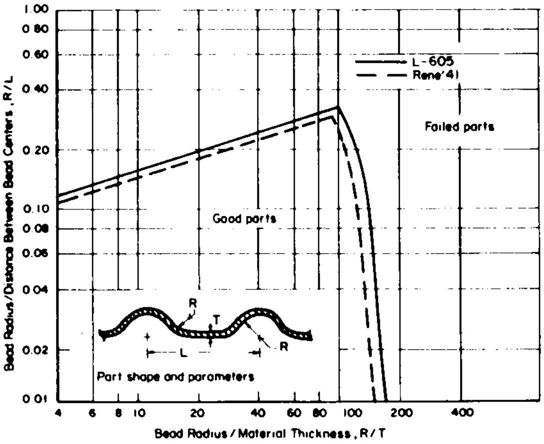


FIGURE 68. CALCULATED FORMABILITY LIMITS OF SOLUTION-ANNEALED RENÉ 41 AND L-605 IN TRAPPED-RUBBER BEAD FORMING (REF. 33)

pressure. The minimum radii that can be formed in 0.020, 0.063, and 0.125-inch-thick material for René 41 and L-605 at various pressures is shown in Figure 67. The figure indicates that increasing the pressure in the range up to 25,000 psi permits forming to smaller radii. Increasing the pressure in the higher range has much less effect on the minimum radius that can be produced by rubber-forming process. The practical limit for both materials appears to be a bead radius of about 2.5 T.

As discussed under drop-hammer forming, failures in beading operations result from splitting or from buckling. Success or failure depends on the ratio of the bead radius to the thickness of the material, R/T, or on the spacing of beads, R/L.

Figure 68 gives the calculated forming limits for beaded panels made by the trapped-rubber process. The experiments used to verify these limits were made with a relatively low forming pressure, 3000 psi. Increasing the forming pressure increases the limiting R/T ratios. The L-605 alloy has a slightly better formability than René 41. This means that beads can be formed with closer spacing, or to smaller radii in sheets of a particular thickness with the L-605 alloy than with René 41.

Two-stage forming can often be used to form parts that cannot be formed entirely in one stage alone. An example of this is the beaded panel that was made of Inconel X-750 alloy in the solution-treated condition shown in Figure 69. Attempting to make the part in one

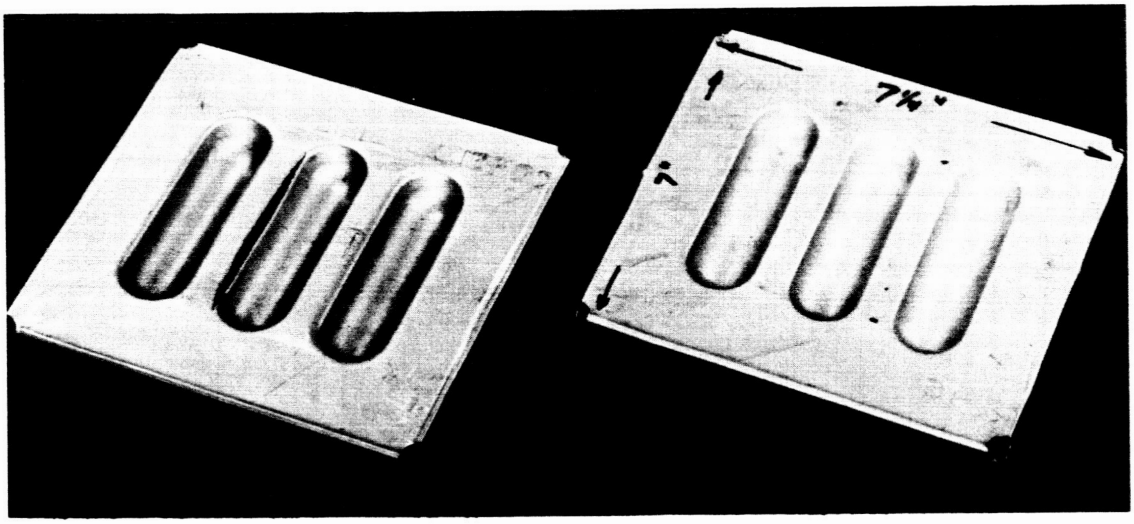


FIGURE 69. TRAPPED-RUBBER-FORMED INCONEL X-750 (REF. 29)

stage caused splitting as shown on the left; a good part was made in two stages as shown on the right, using a vaseline lubricant on the die surface. The maximum calculated strain was 37 to 40 per cent across the part surface. Material is a 0.025-inch as-received sheet.

STRETCH FORMING

Introduction. In stretch forming, the workpiece, usually of uniform cross section, is subjected to a suitable tension and then wrapped around a die of the desired shape. Deformation occurs mainly by bending at the fulcrum point of the die surface. Compression buckling is avoided by applying enough tensile load to produce approximately 1 per cent elongation in the material. The tensile load shifts the neutral axis of the workpiece toward the forming die.

The terms linear stretch forming and stretch-wrap forming denote operations on preforms such as extrusions or brake-formed parts. Figure 70 illustrates two types of linear stretch forming. The classification is based on the position of the flange in the plane of forming. Depending on its location the flange is stressed in either tension or compression. Although the sketch shows an angle, the same classification is used when forming channels and hat sections. A typical linear stretch-forming operation for making bent "T" sections is shown in Figure 71.

Stretch forming is also used for producing double contours in sheet. Ordinarily, the sheet is stretched and bent around a male die with convex curvature. In a second double-contouring technique, called Androforming, the sheet is pressed between matched dies after the tensile load has been applied. This type of stretch forming is illustrated in Figure 72.

Equipment Used for Stretch Forming. Presses with a capacity range of 5 to 5000 tons are used for stretch forming sheet and sections. The small capacity machines are generally used for linear stretch forming of light sections while the larger capacity machines are used either for sheet and plate or heavy sections. The specifications of some commercially available equipment for stretch forming are given in Table XXV. Equipment that could be used to stretch form annealed-nickel- or cobalt-base-alloy plate 14 x 20 foot and 1/2 inch thick with a capacity of 6000 tons has been proposed (Ref. 64).

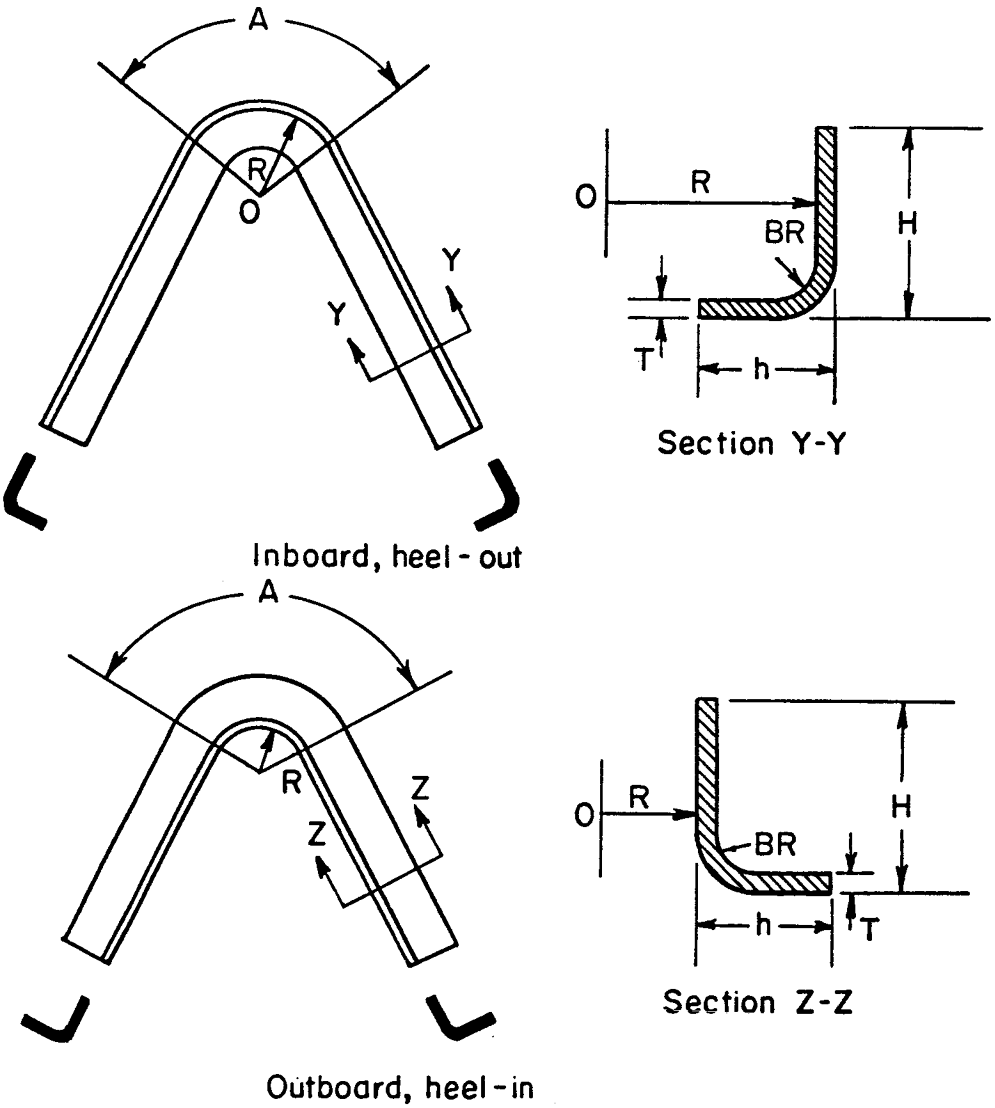


FIGURE 70. PARAMETERS OF HEEL-IN AND HEEL-OUT LINEAR-STRETCH-FORMED ANGLES

R = stretch die radius	H = heel dimension
BR = brake formed radius	A = forming radius
h = flange dimension	T = thickness of material

Courtesy of North American Aviation, Inc.

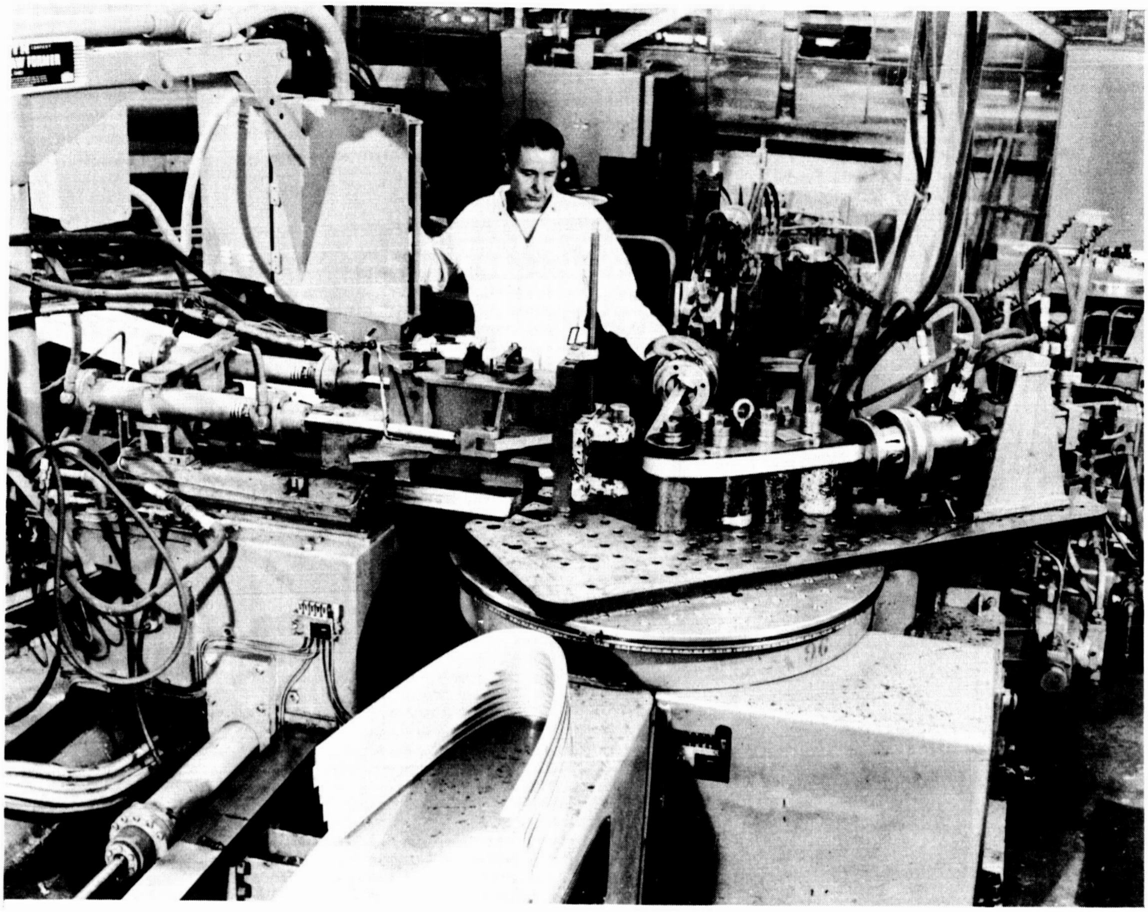


FIGURE 71. STRETCH-FORMING MACHINE FOR SECTIONING

In-board or heel-out "T" sections are being formed.

Courtesy of Cyril Bath Company, Solon, Ohio.

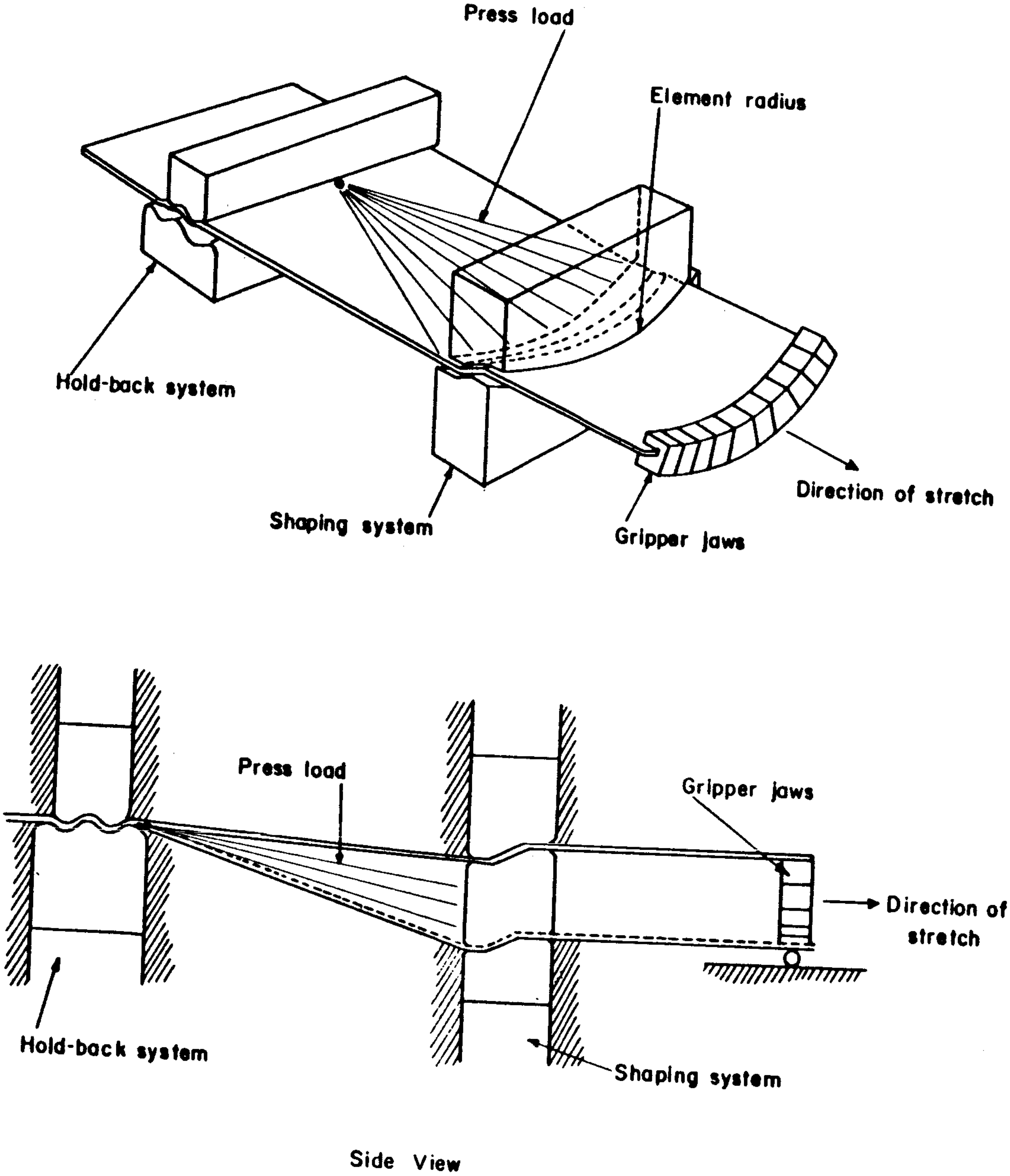


FIGURE 72. ANDROFORM MODIFICATION OF THE STRETCH-FORMING PROCESS (REF. 33)

TABLE XXV. CAPABILITIES OF TYPICAL STRETCH-FORMING MACHINES

Tonnage[a]	Rate of Forming, deg/min	Material Size, inches	Type
		Cyril Bath (Ref. 65)	
200-2000	--	84-144 width	Sheet stretch
150	36 max	--	Sheet or section stretch
100	36 max	--	Section stretch
75	36 max	--	Section stretch
50	36 max	--	Sheet or section stretch
25	50 max	--	Section stretch
10	90 max	--	Section stretch
250 pressing 85 stretching	--	Bed 138 x 128	Stretch draw sheet
		Sheridan-Gray (Ref. 66)	
5	--	16-96	Section
10	--	16-144	Section
21	--	18-144	Section
54	--	28-216	Section
104	--	40-288	Section
306	--	48-288	Section
59	220 max	20-336	Sheet stretch
120-5000 stretching	--	48-240 width	Sheet stretch draw[b]
300-1000	--	96-360 length	Sheet stretch draw[b]

(a) All tonnage for stretch unless otherwise noted.

(b) Presses similar to Androforming.

The press in Figure 73 employs the stretch-draw principle to form parts with irregular contours. A 250-ton machine of this kind is capable of making parts that would require a 900-ton double-acting, deep-drawing press.

Tooling. The tooling for stretch forming normally consists of a male die made to the contour and dimensions desired in the final part. A number of materials have been used for tooling depending on the number of parts to be made. For room-temperature linear stretch forming of sections, a composite steel die with inserts that will accommodate different thicknesses of material is often used. Tooling of this kind is shown in Figure 74. The method of using die inserts and shims to adjust for various thicknesses of materials and angle-leg lengths, as shown in Figure 75, permits the number of different size tooling sets to be significantly reduced.

For room-temperature operations on sheet, the tooling can be made from zinc-base alloys (Kirksite) or from concrete faced with plastic. Cast-aluminum tooling faced with a 3/4-inch layer of epoxy resin can be used for larger production quantities. The life of the stretch-forming tooling can be extended by first stretch forming a thin sheet of stainless steel over the tool and then forming over the stainless. This should be done when Kirksite tooling is used and the nickel or cobalt alloys are to receive a subsequent thermal treatment.

The grips for stretch forming should be made of hardened tool steel with sharp clean serrations. This is particularly important when a number of grips are used as in forming sheet. If the grips are not in good mechanical working condition, the workpiece may slip in some locations and tear at the grips that apply a greater holding force. Relieving the first four teeth near the jaw edges by polishing or grinding helps to prevent premature tearing of the sheet.

Techniques of Stretch Forming. In stretch forming, skilled operators and careful attention to details are essential for success. Trouble may result from exceeding the uniform elongation of the material. Since most nickel- and cobalt-base alloys have good uniform elongation, they stretch form with a minimum of difficulty.

The preformed sections or sheet material, in either the solution-treated or annealed condition, are first loaded into the clamping jaws of the stretch press. A load is then applied to the material to produce at least 1 per cent extension at the grips. The grips are then either rotated around the die as in section forming or pulled against the die in sheet forming, and the load is increased slightly to assure

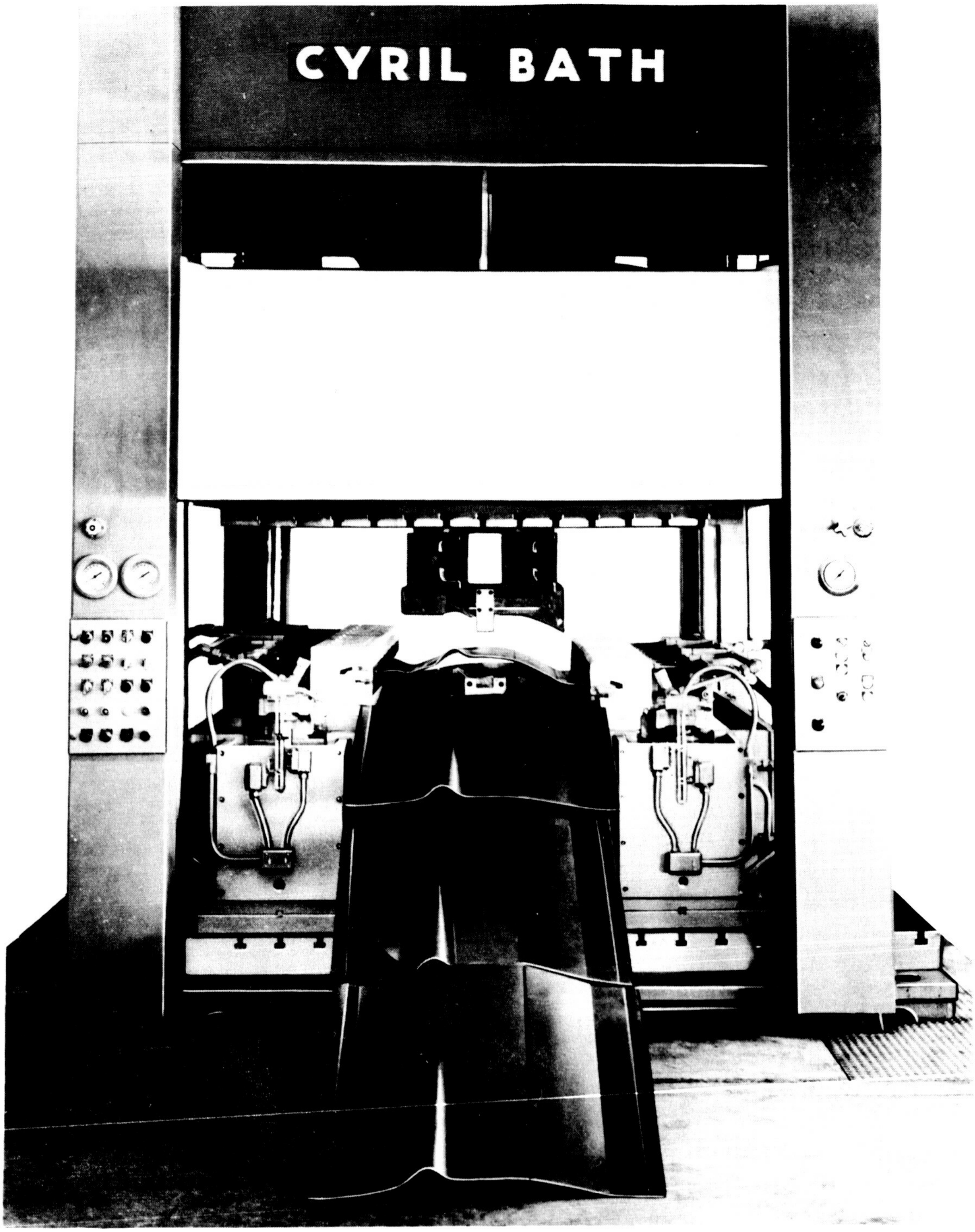


FIGURE 73. STRETCH-DRAW-PROCESS MACHINE FOR SHEET

250-ton pressing, 85-ton stretching.
Courtesy of Cyril Bath Company, Solon, Ohio.

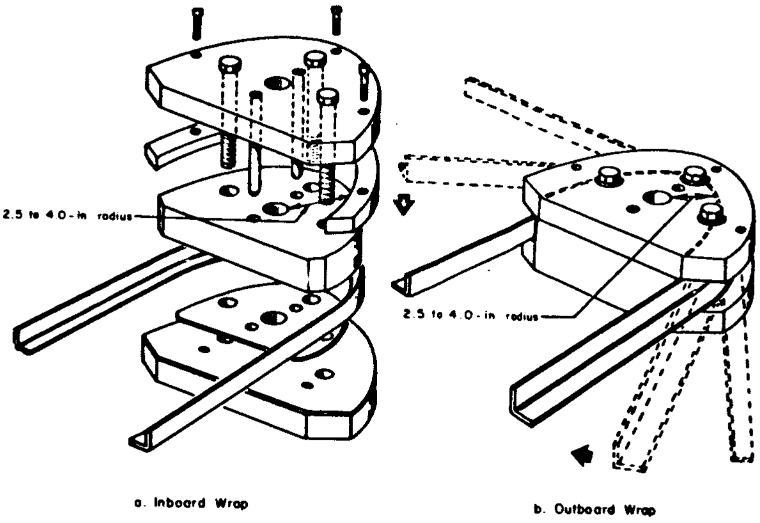


FIGURE 74. STRETCH-MACHINE (ANGLE SECTIONS) TOOLS

Courtesy of North American Aviation, Inc.

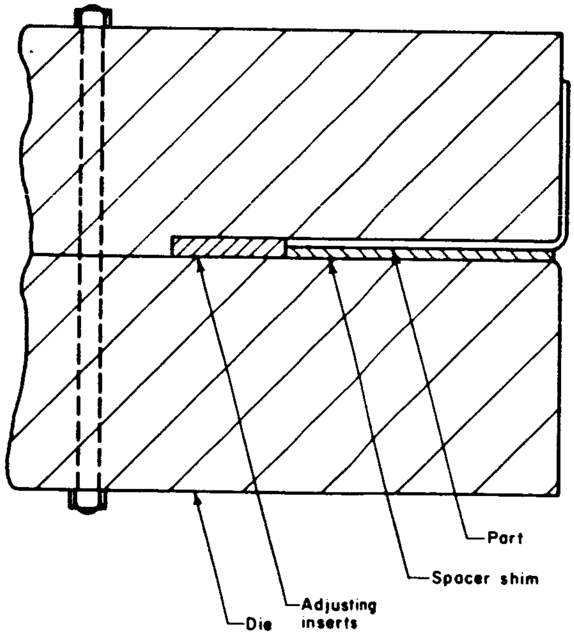


FIGURE 75. SECTIONAL VIEW OF LINEAR STRETCH TOOLING FOR HEEL-OUT ANGLES (REF. 26)

that the part conforms with the die. The rate of movement against the die may be as high as 10 degrees per minute. After the material is in complete contact with the die over the entire area to be formed, the stretching load is again increased to minimize springback. Since some springback usually results from room-temperature stretch forming of nickel- and cobalt-base alloys, the machine is generally adjusted for overforming to compensate for this. In forming sections, a springback from 5 to 10 per cent of the bend angle can be expected for annealed material.

To obtain maximum formability in stretch forming, the material should be stretched with the rolling direction of the material. For preformed angles, channels, or hat sections, this requires that the prior operation be performed across the rolling direction of the material.

When severe deformation is required, multistage forming with intermediate anneals may be used. Stretch forming of nickel- and cobalt-base alloys is normally carried out at room temperature. The curves for the stretch-formability index of René 41 and L-605 given in Figure 76 indicate a decrease in formability with increasing temperatures from room temperature to 2000 F.

Lubricants have been found to have very little effect in stretch forming because of the relatively small movement of the material over the die.

Blank Preparation. For room-temperature stretch forming, the blanks should have clean surfaces. Blanks with as-sheared edges are used provided burrs are removed to prevent tooling damage. Sections to be linear stretch formed should be cleaned after brake forming and stress relieved or annealed for maximum formability. Any surface contamination from the brake-forming operation or thermal treatment should be removed by acid etching as described under the section on blank preparation. Where the maximum available sheet size is required to make a part, tabs may be welded onto the sheet for the grip area. A reduction in strength due to the welding may limit the amount of stretching possible by this method.

Nickel- and Cobalt-Base-Alloy Stretch-Forming Limits. Success or failure in stretch forming a material to a particular shape depends on its mechanical properties and on the severity of the forming. Failures occur from buckling or from splitting, as illustrated in Figure 77. The geometrical factors controlling the difficulty in forming of a section are the thickness, the height of the workpiece in

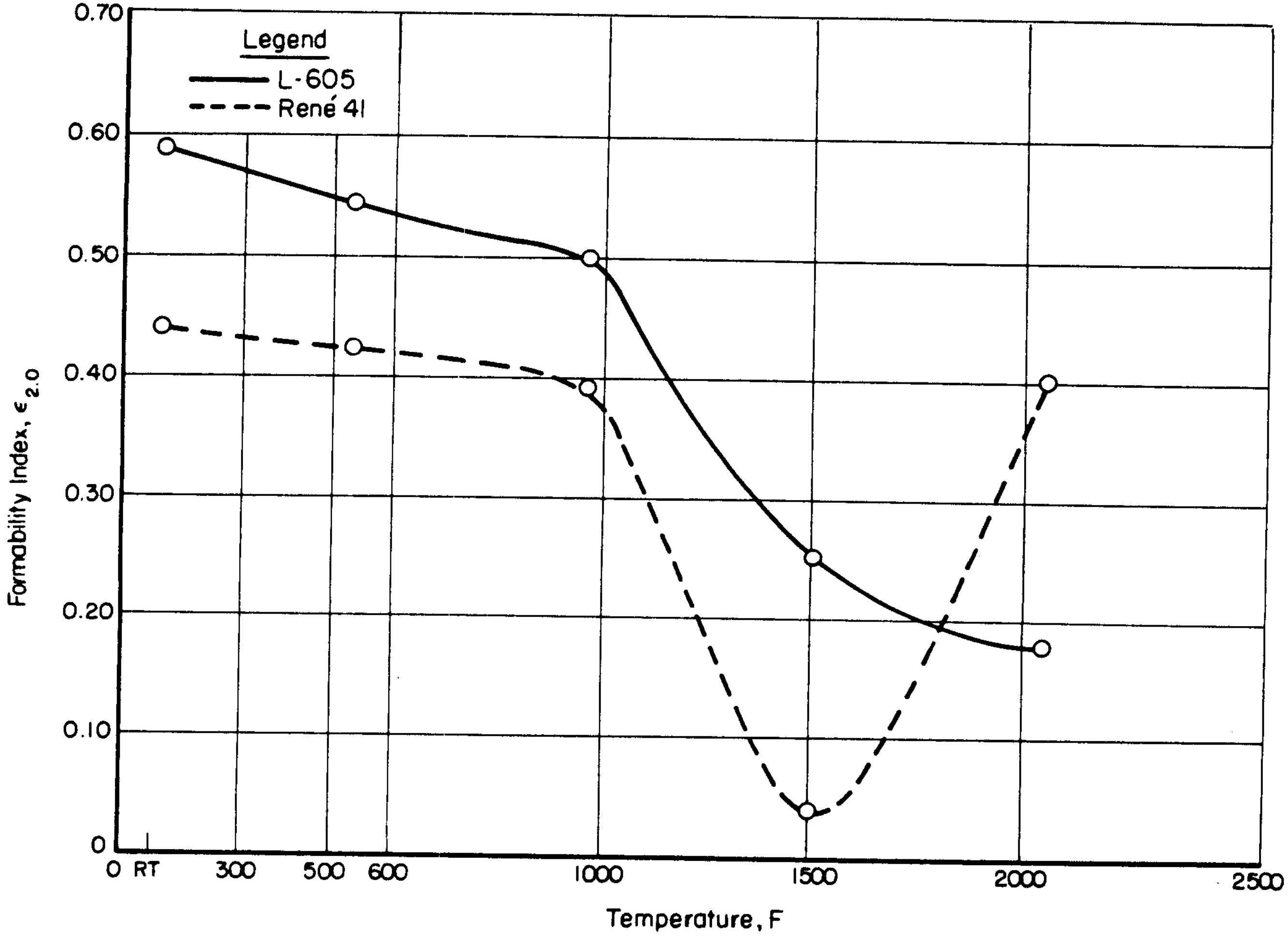


FIGURE 76. OPTIMUM FORMING TEMPERATURE CURVES FOR LINEAR STRETCH AND SHEET STRETCH (REF. 25)

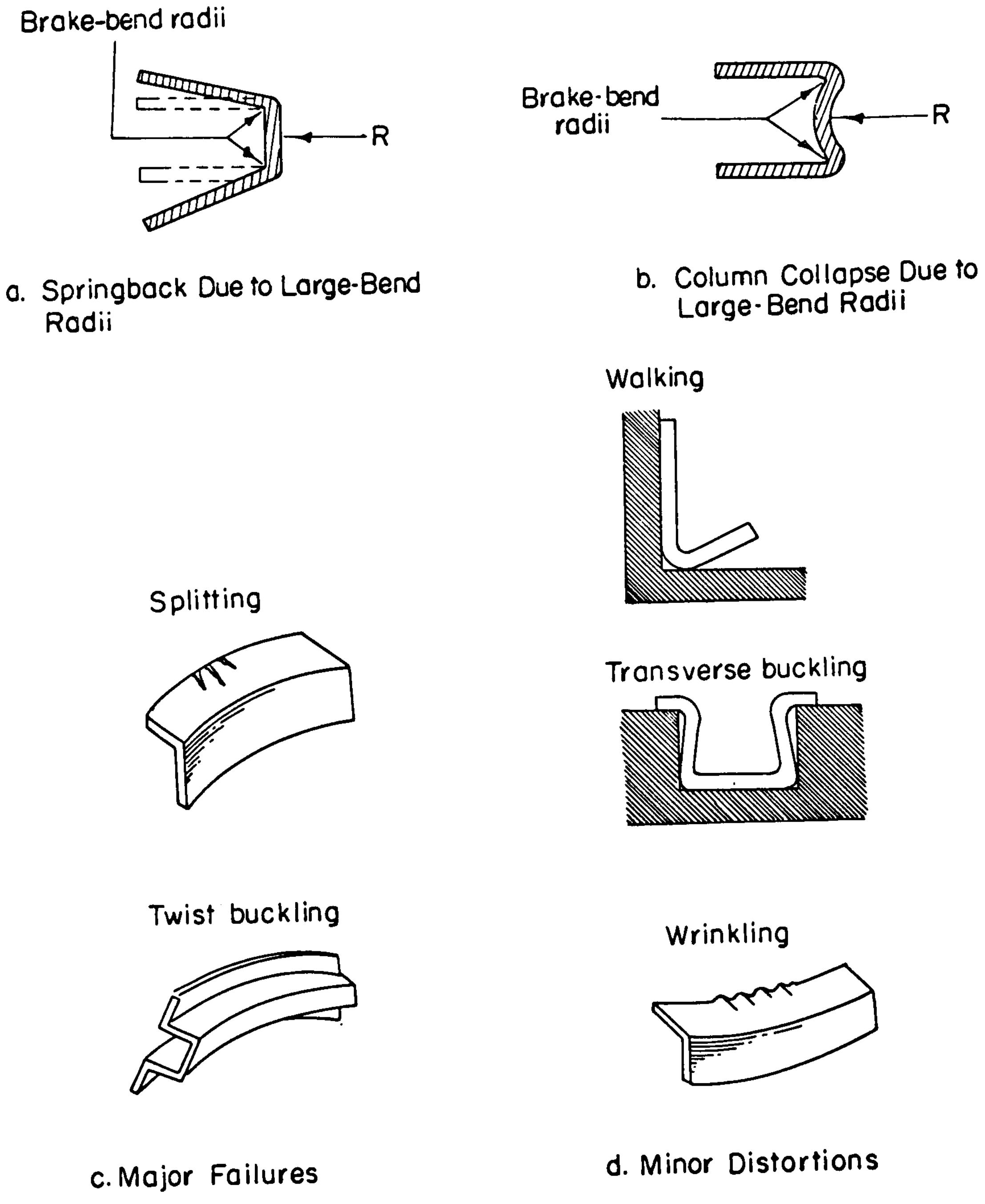


FIGURE 77. TYPES OF FAILURES FOR LINEAR STRETCH FORMING (REF. 25)

the plane of bending, and the radius of the stretch-forming die. The important characteristics of the workpiece material are its capacity for stretching without rupture and its ratio of elastic modulus to yield strength. These mechanical properties influence splitting and buckling, respectively. Wood (Ref. 25) demonstrated that the amount of stretching a material will withstand before splitting correlates with elongation, in a 2-inch gage length, in tensile tests. The maximum per cent stretch in a particular operation is generally determined by the flange dimensions in the plane of forming of the section divided by the inside radius of the bend times 100. For example, the elongation would amount to 10 per cent for a section with a 1-inch flange formed around a 10-inch radius.

Wood and associates (Refs. 25,26,33) predicted splitting and buckling limits in René 41 and L-605 alloys in stretch forming. The predictions were based on analysis of the mechanics of the operations and a knowledge of mechanical properties exhibited in tensile tests. The formability limits were checked by forming good parts within the limits and failed parts beyond the limits.

Figure 78 shows the forming limits for heel-in or outboard stretch forming of René 41 and L-605 sections. The L-605 alloy can be stretched more, without splitting, than the René 41 alloy. This is indicated by the relative H/R ratios, which reflect ductility and ability to stretch. The same relative formability is shown when buckling rather than splitting is more likely to control failure.

Figure 79 gives the formability limit curves for heel-out, or inboard, stretch forming of angle and channel sections. This change in part orientation causes a shift in the limiting H/R and H/T ratios because it affects the severity of deformation. The relative order of formability between the materials is not changed because it depends on their mechanical properties.

The formability limits of hat sections in the heel-in position are shown in Figure 80. The buckling limits are a little higher than for angles and channels because the flange on the hat gives some support during forming.

Elongation is the material property affecting success in stretch forming sheet. Thickness has little or no effect. In double-contour forming of sheet, the radii of curvature and their chord lengths are the geometrical factors controlling the limits of deformation. The products of the two limiting ratios of the radii to their chords is a

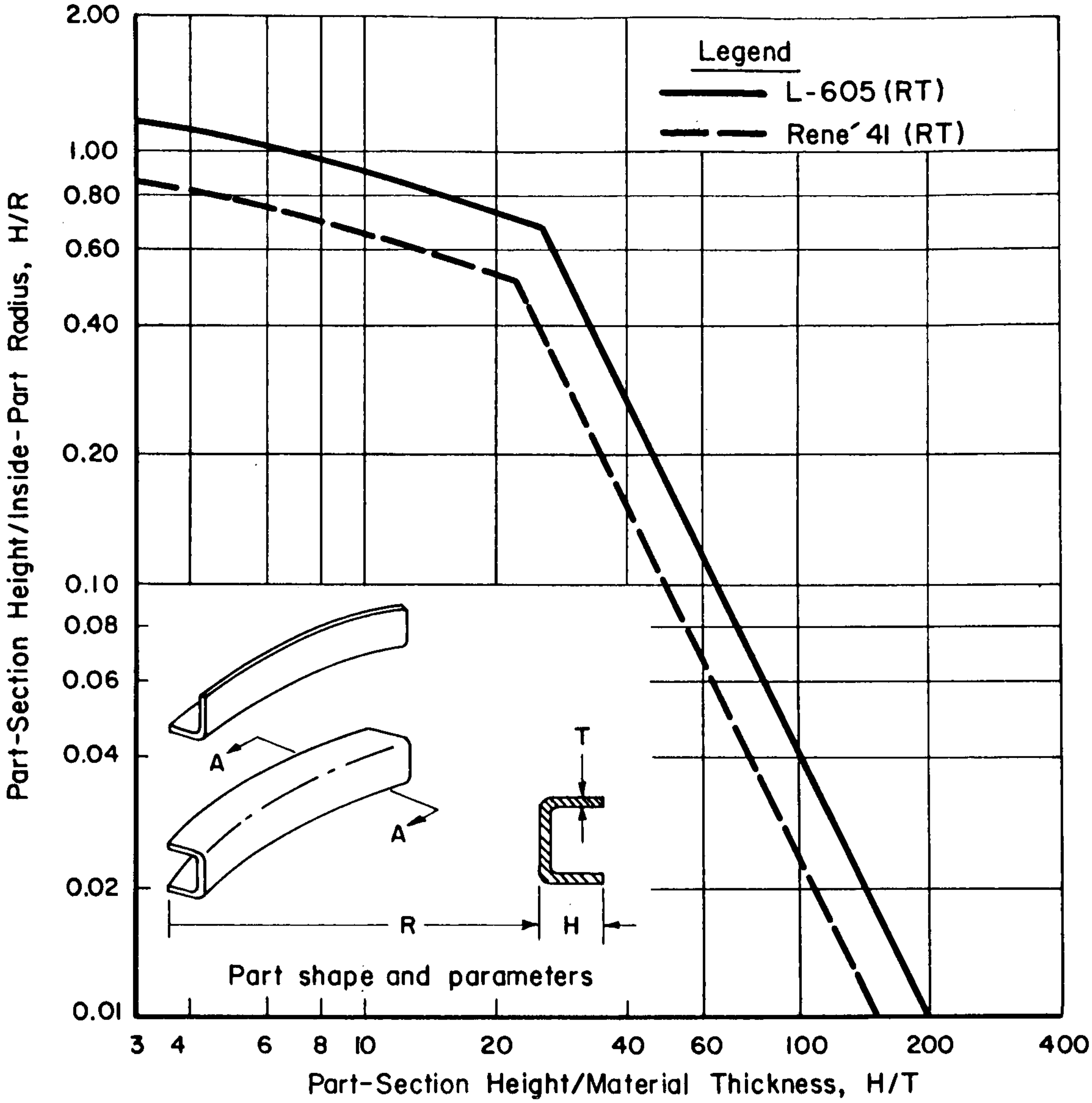


FIGURE 78. ROOM-TEMPERATURE LIMIT CURVES FOR LINEAR-STRETCH HEEL-IN ANGLE AND CHANNEL SECTIONS OF RENÉ 41 AND L-605 (REF. 25)

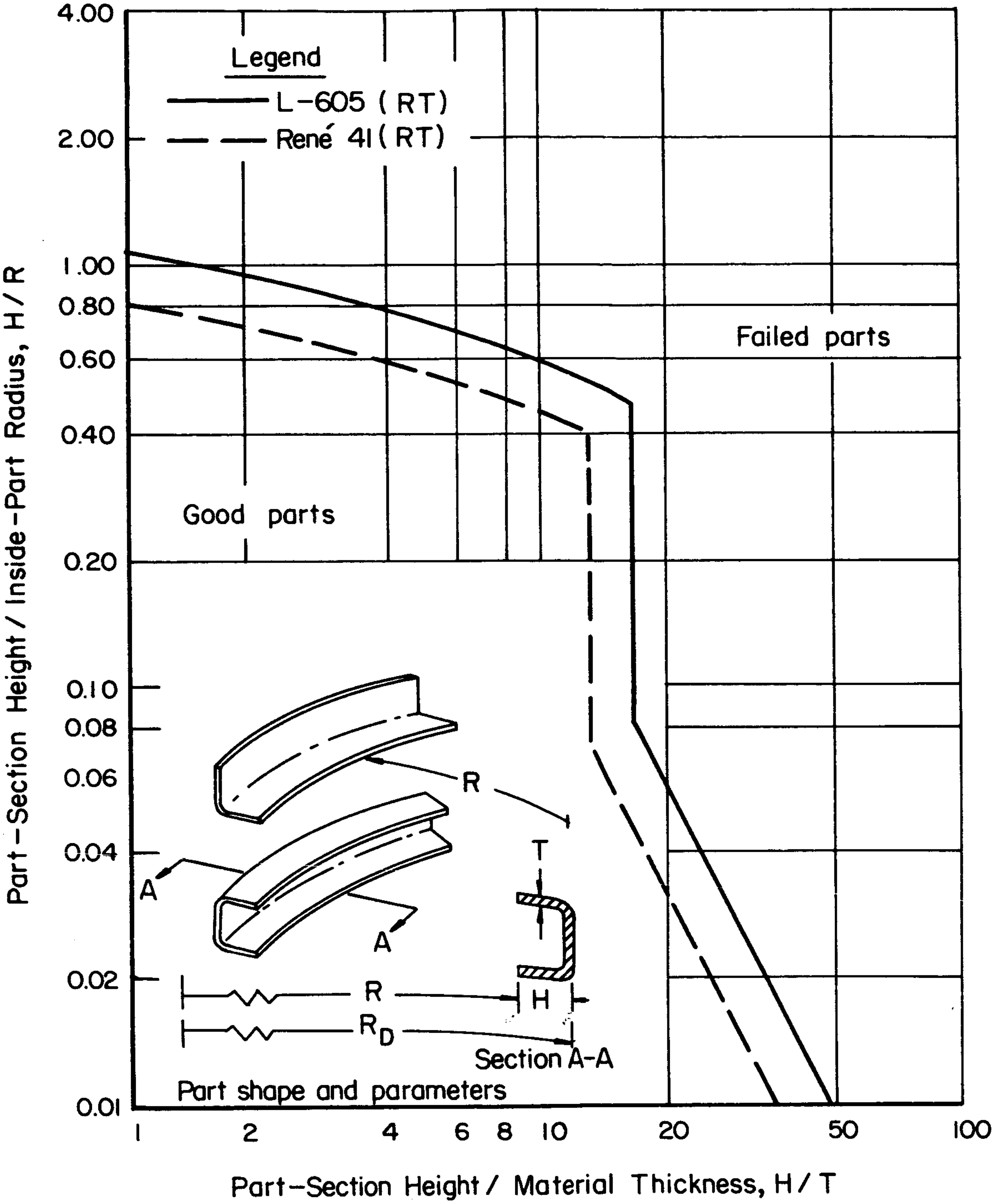


FIGURE 79. ROOM-TEMPERATURE LIMIT CURVES FOR LINEAR-STRETCH HEEL-OUT ANGLES AND CHANNELS OF RENÉ 41 AND L-605 (REF. 25)

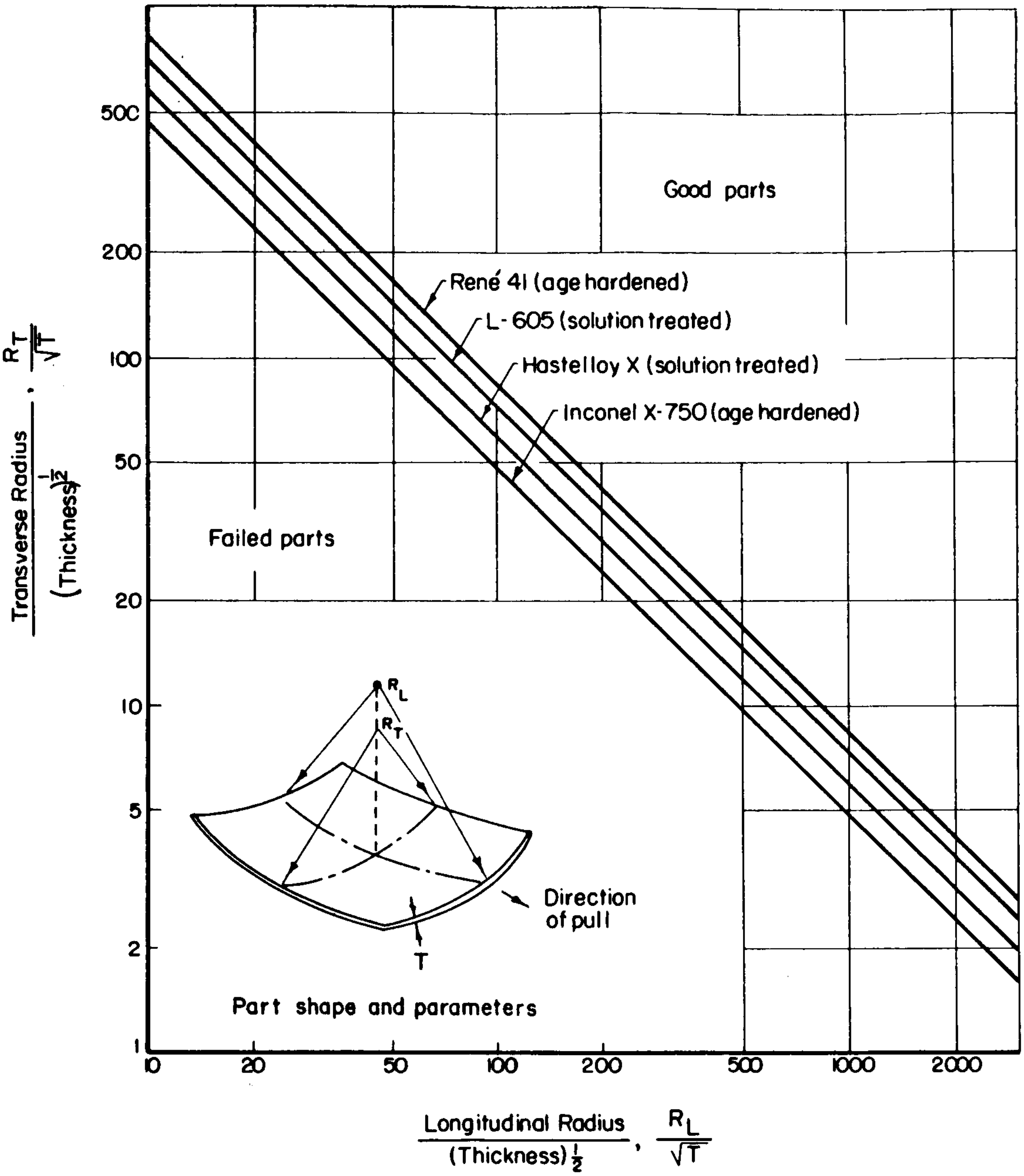


FIGURE 80. ROOM-TEMPERATURE LIMIT CURVES FOR LINEAR-STRETCH HEEL-IN HAT SECTIONS OF RENÉ 41 AND L-605 (REF. 25)

constant for a particular material and forming temperature at maximum possible deformation; that is, using the terminology illustrated in Figure 81

$$\left(\frac{R_L}{L}\right)\left(\frac{R_T}{T}\right) = \text{Constant} \quad . \tag{21}$$

The tensile load should be applied in the direction necessary to stretch the sheet over the smaller radius because this requires more elongation. The blank should be oriented so the pull is applied in the direction in which the sheet is more ductile. Usually, this is parallel to the major direction of extension in rolling.

Figure 81 also shows the stretch-forming limits for René 41 and L-605. The limits, expressed in ratios of die radii to chord lengths, are based on elongation values in room-temperature tensile tests. Although the difference is small, the L-605 alloy is expected to show better forming properties than René 41.

In Androforming sheets between matched dies, shaping-system elements (Figure 82) permit the forming of smaller contour radii. Unlike simple stretch forming, however, thickness as well as ductility is important because failure can result from either buckling or splitting. Therefore, the parameters used to define forming limits in Figure 82 include an allowance for sheet thickness. The limiting ratios for several nickel- and cobalt-base alloys are given in Figures 82 through 85 for two different size forming elements. Changing from a 50-inch to a 20-inch forming element lowers the limiting parametric ratios. The room-temperature limit curves in Figures 82 and 83 indicate that Inconel X-750 in the age-hardened condition is less likely to buckle or split in Androforming than the L-605 alloy in the solution-treated condition.

Stretch-forming trials conducted by Germann and Shaver (Ref. 29) indicated that Inconel X-750 could be stretched up to 40 per cent in the annealed condition and 20 per cent in the aged condition. Some of the specific values for two different thicknesses of material are given in Table XXVI.

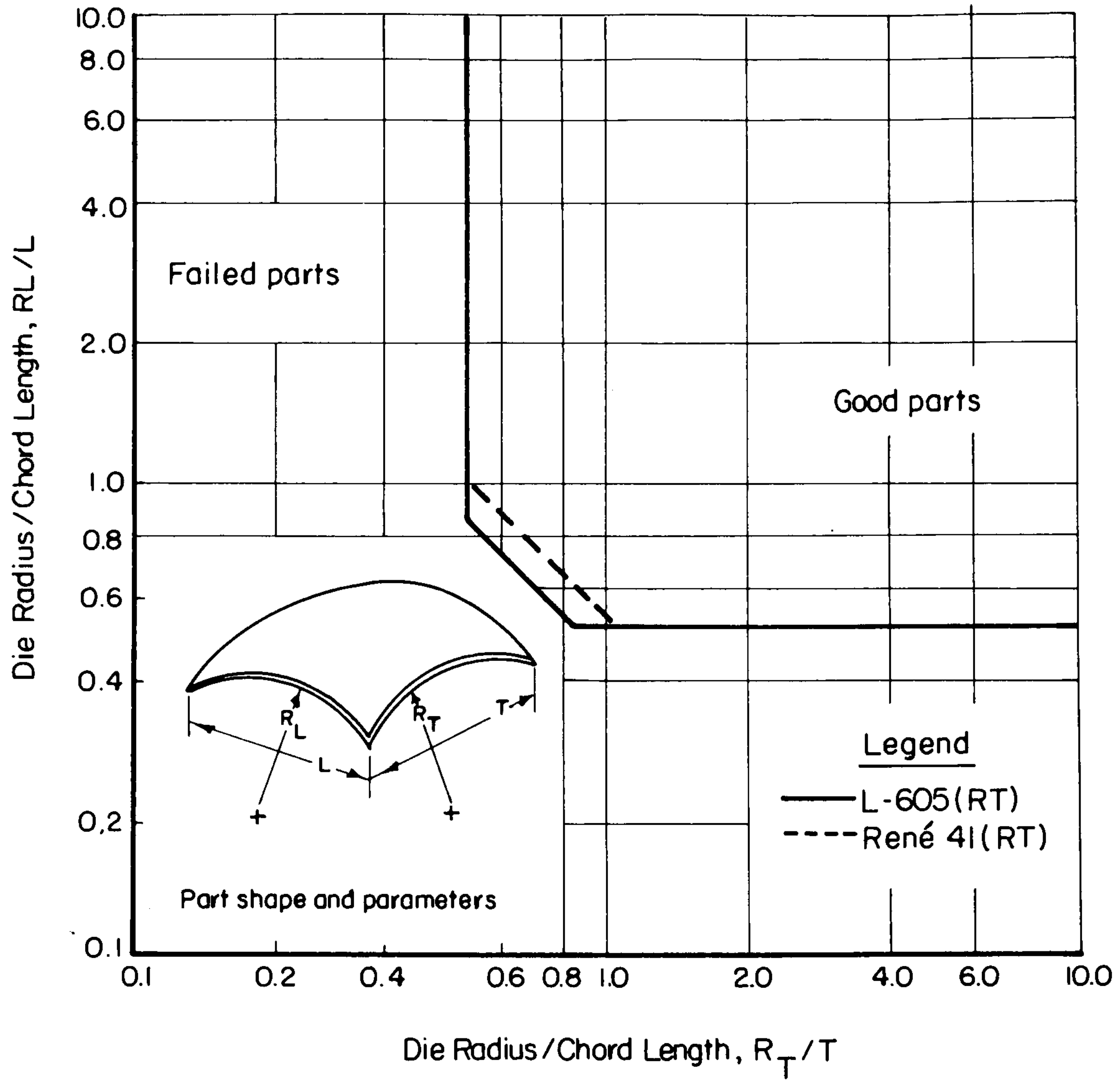


FIGURE 81. ROOM-TEMPERATURE LIMIT CURVES FOR SHEET STRETCH OF RENÉ 41 AND L-605 (REF. 25)

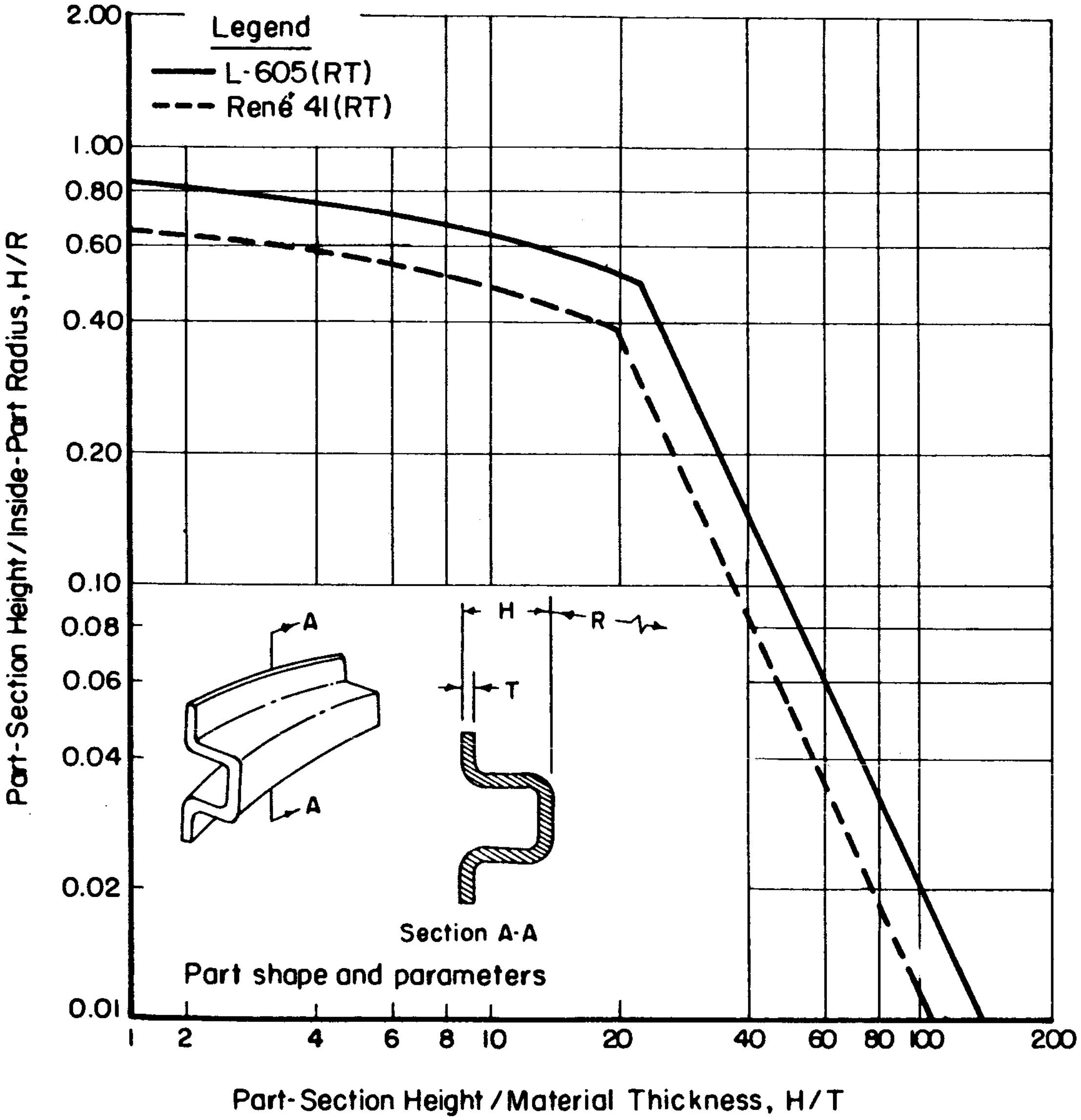


FIGURE 82. COMPOSITE GRAPH FOR ANDROFORM SPLITTING LIMITS FOR 50-INCH FORMING ELEMENT (REF. 33)

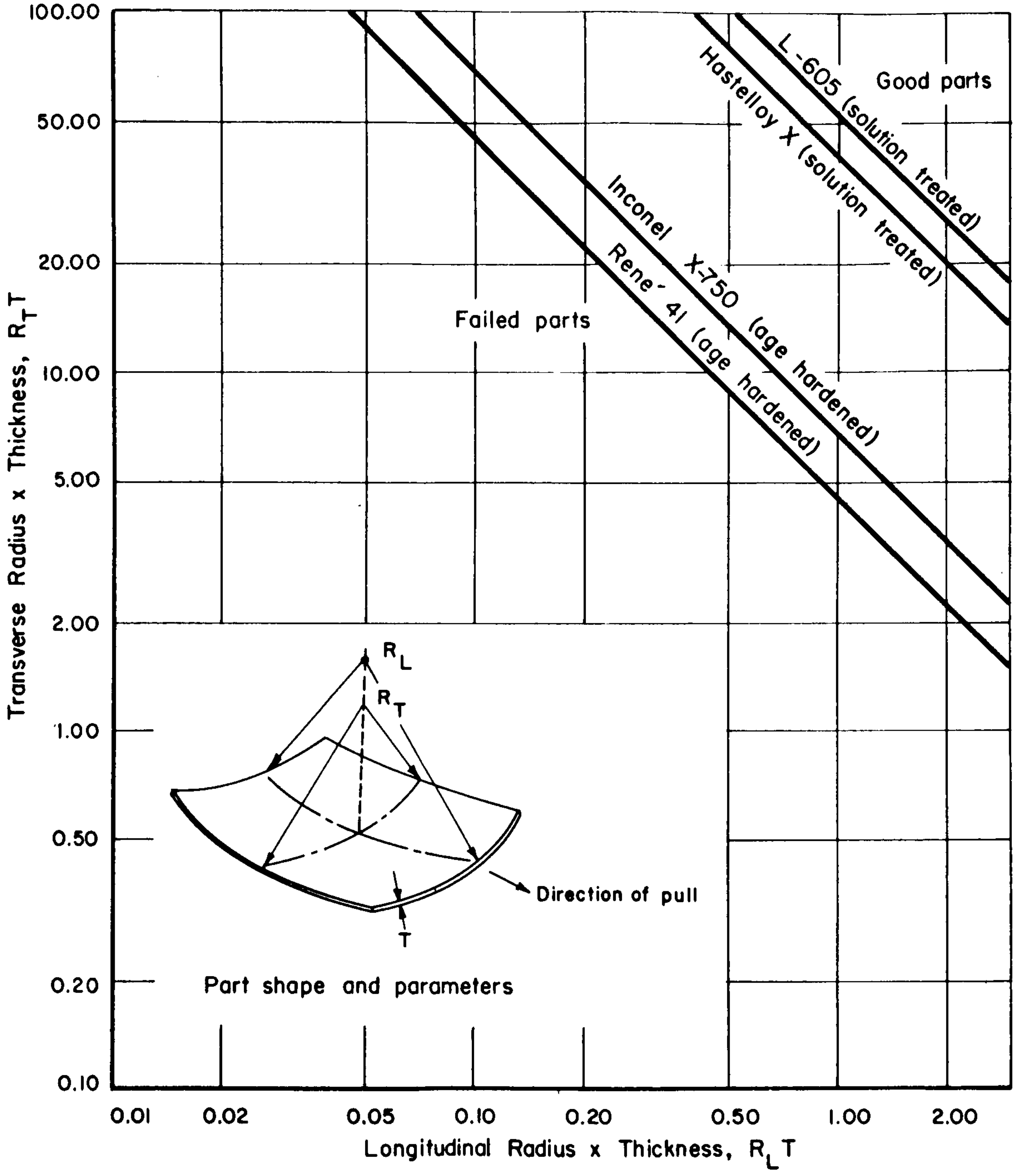


FIGURE 83. COMPOSITE GRAPH FOR ANDROFORM BUCKLING LIMITS FOR 50-INCH FORMING ELEMENT (REF. 33)

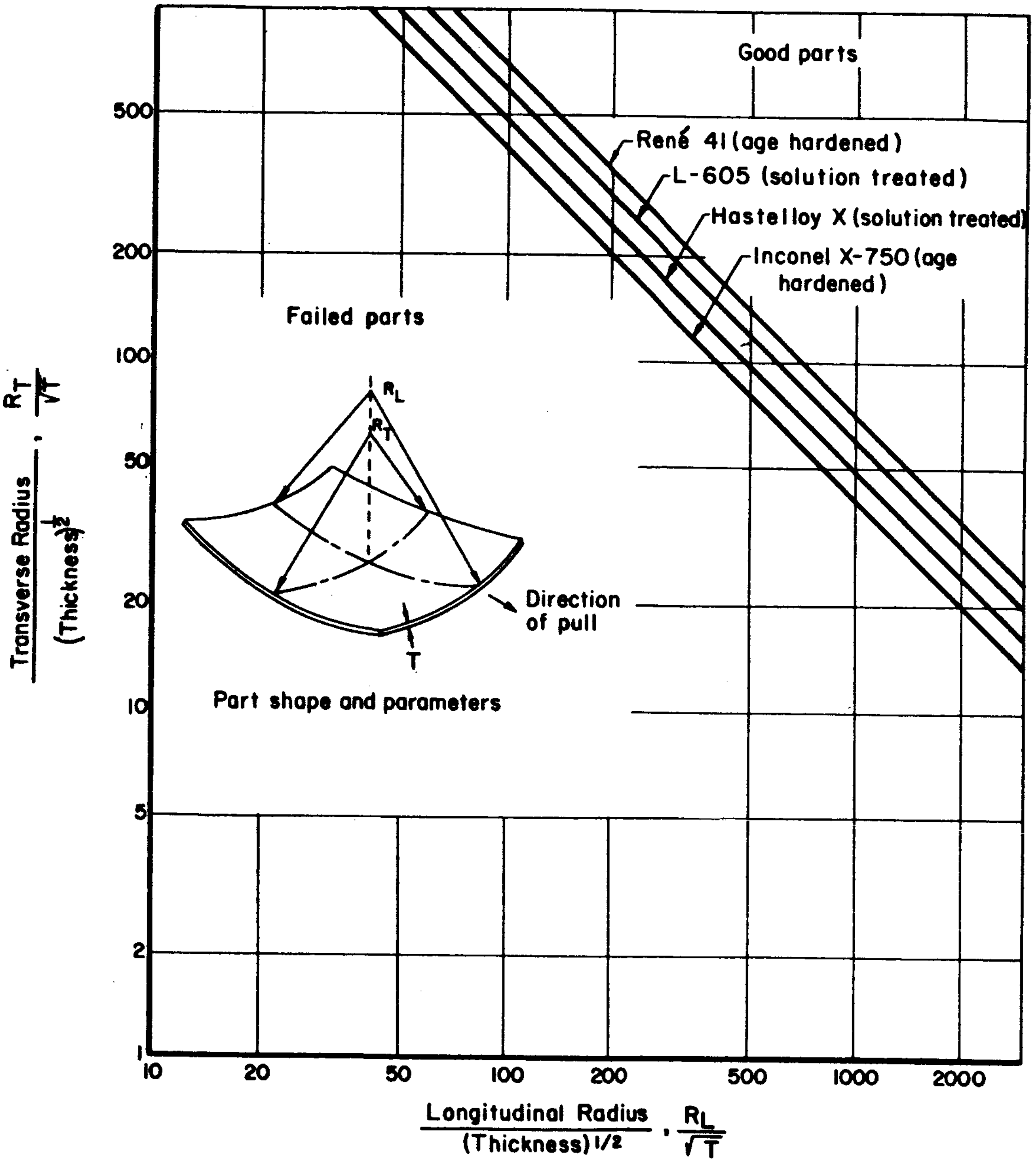


FIGURE 84. COMPOSITE GRAPH FOR ANDROFORM SPLITTING LIMITS FOR 20-INCH FORMING ELEMENT (REF. 33)

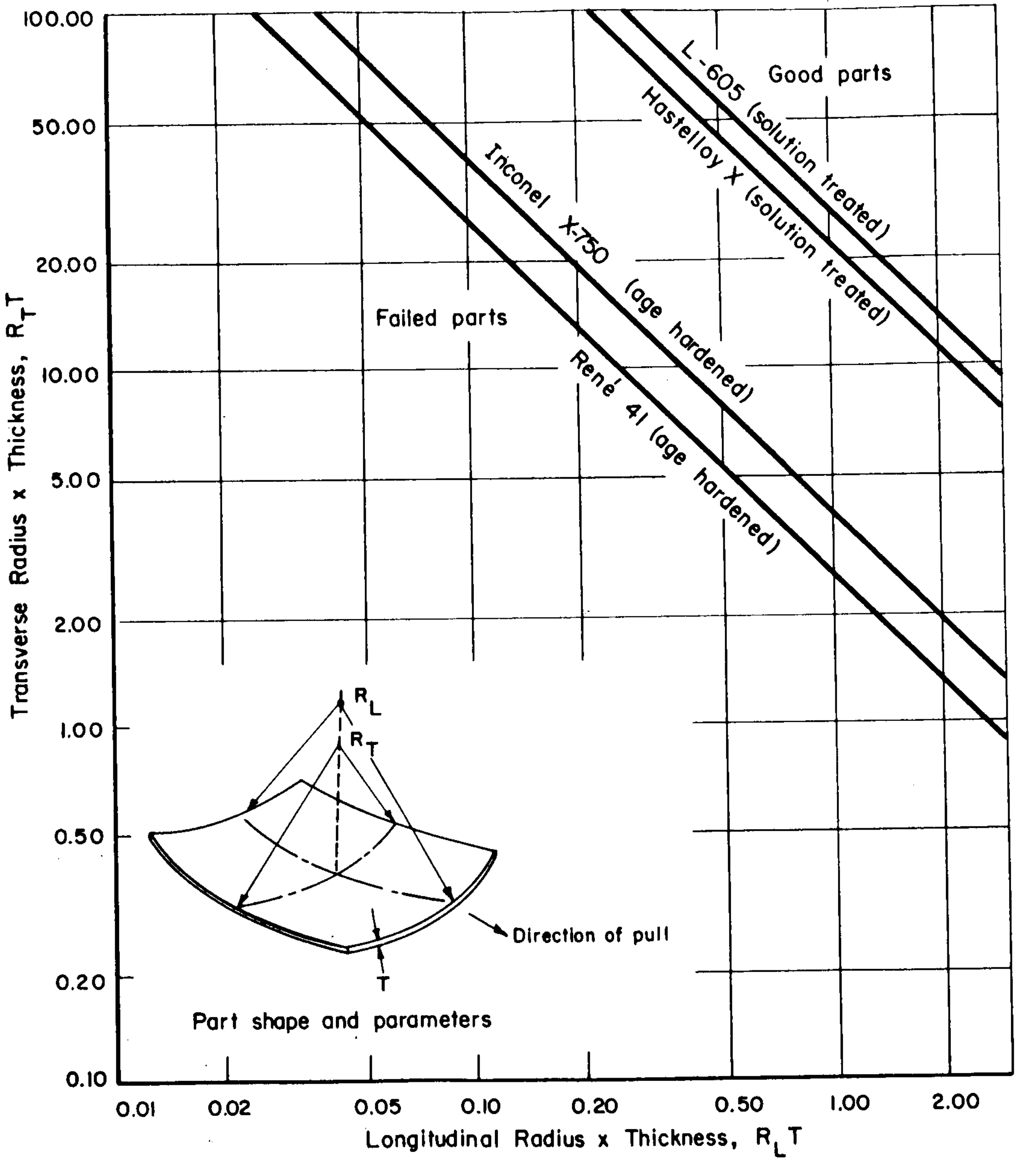


FIGURE 85. COMPOSITE GRAPH FOR ANDROFORM BUCKLING LIMITS FOR 20-INCH FORMING ELEMENT (REF. 33)

TABLE XXVI. STRETCH-WRAP AND FORMING DATA FOR INCONEL X-750 (REF. 29)

Tool or Die	90-Deg Angles With 1-Inch Flanges Test Specimen	Pull in Pounds	Per Cent Elongation	Remarks
Straight pull	0.062 in. x 5 ft (aged)	4800	13.5	--
	0.062 in. x 5 ft (annealed)	1650	37.1	Local yielding
Ditto	0.093 in. x 5 ft (aged)	6300	15.3	--
	0.093 in. x 5 ft (annealed)	1850	41.8	Local yielding
"	0.062 in. x 3 ft (aged)	4500	--	Ruptured
	0.093 in. x 3 ft (annealed)	1800	44.0	Local yielding
Contour die 15-in. diam	0.062 in. x 5 ft (aged)	4600	20.0	2-deg springback
	0.093 in. x 5 ft (aged)	6800	19.5	3-1/2-deg springback
Contour die 15-in. diam	0.062 in. x 5 ft (annealed)	1650	38.0	Slight local yielding
	0.093 in. x 5 ft (annealed)	1900	42.0	Ditto

Lloyd and Lake conducted stretch-forming tests on a number of nickel-base alloys (Refs. 37-39). They concluded that Waspaloy had the best formability, followed by M-252; Udimet-500 and R-235 alloy were poorer, and about the same. All four materials could be stretch formed between 30 and 40 per cent in the annealed condition at room temperature. A typical stretch-formed angle made from R-235 alloy is shown in Figure 86. The part was made at room temperature from 0.063-inch sheet in the annealed condition. Both flanges on the angle were 1 inch wide, and the part was stretch formed slightly more than 180 degrees on a 6-1/2-inch radius.

TUBE FORMING

Introduction. Because of their high strength at elevated temperatures, tubular parts of nickel- and cobalt-base alloys are being used for ducting on jet engines. They are also used extensively for handling corrosive chemicals. Forming operations are necessary for producing reduced sections, bulges, bends, etc. The problems in tube forming generally become more difficult as the diameter of the tube is increased and the wall thickness is decreased. Some of the current methods for forming nickel- and cobalt-base-alloy tubing are described in this section.

Tube Bending. The four major methods in general use for bending tubes are: (1) ram or press bending, (2) roll bending, (2) compression bending, and (4) draw bending. These are depicted

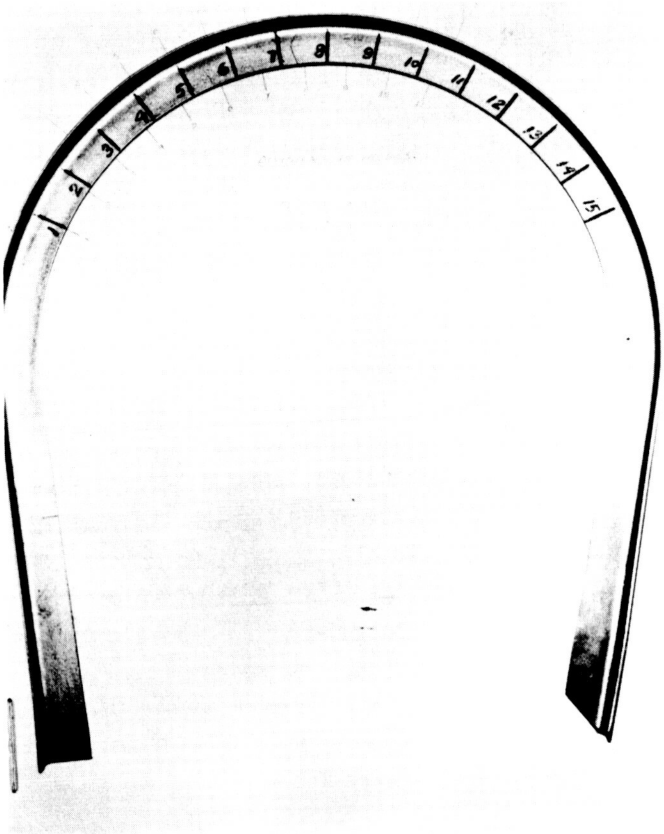


FIGURE 86. STRETCH-FORMED R-235 ANGLE 1-INCH FLANGES, 0.063 MATERIAL, 6-1/2-INCH RADIUS (REF. 39)

schematically in Figure 87. Ram or press bending is accomplished by placing the tube between two supports and pressing the ram and tube between the supports, thus forcing the tube to bend around the ram. Roll bending is accomplished by passing the tube through a suitable series of grooved, power-driven rolls. In compression bending, both the tube and the die are stationary and a wiper die is utilized to wrap the tube around the stationary bend die. The first three methods are used for heavy-wall tubing or tubes filled with a matrix material since they are likely to cause thin-wall tubing to wrinkle, fracture, or even collapse. They are generally limited to forming generous bend radii usually more than five times the tubing diameter (Ref. 49). The fourth method, draw bending, is used to bend thin-walled tubing and to obtain bend radii as small as 1.5 D. The tube is confined during bending, and is supported internally by a flexible mandrel.

Each method of bending has special limitations that often control the success or failure of the operation. Generally speaking the processes can be used for the operations shown in Table XXVII. Since the nickel- and cobalt-base alloys have similar room-temperature forming properties to the stainless steels it is possible to make a comparison with the known forming characteristics of the stainless tubing in bending. Figure 88 shows the various stainless steel tube sizes that can be bent by the different tube-bending processes.

TABLE XXVII. LIMITS OF VARIOUS TUBE-BENDING PROCESSES (REF. 67)

Bending Process	Types of Bends Usually Accomplished	Maximum Angle of Bend, degrees
Ram or press	Single bends Tube straightening	<120
Roll	Circular Spirals Helical coils	360
Compression	Single bends	<180
Rotary draw	Single Multiple Compound	180

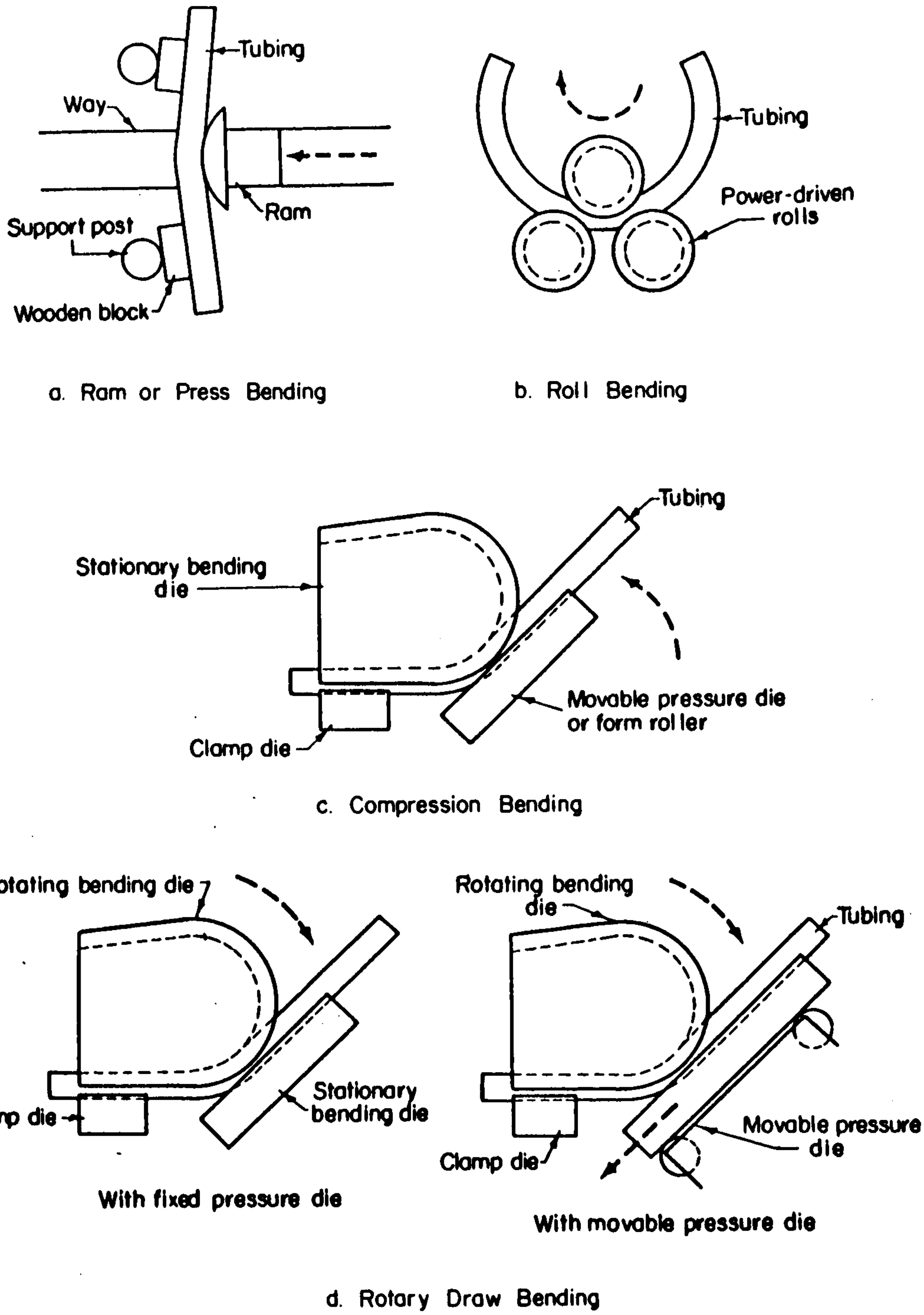


FIGURE 87. METHODS OF TUBE BENDING (REF. 67)

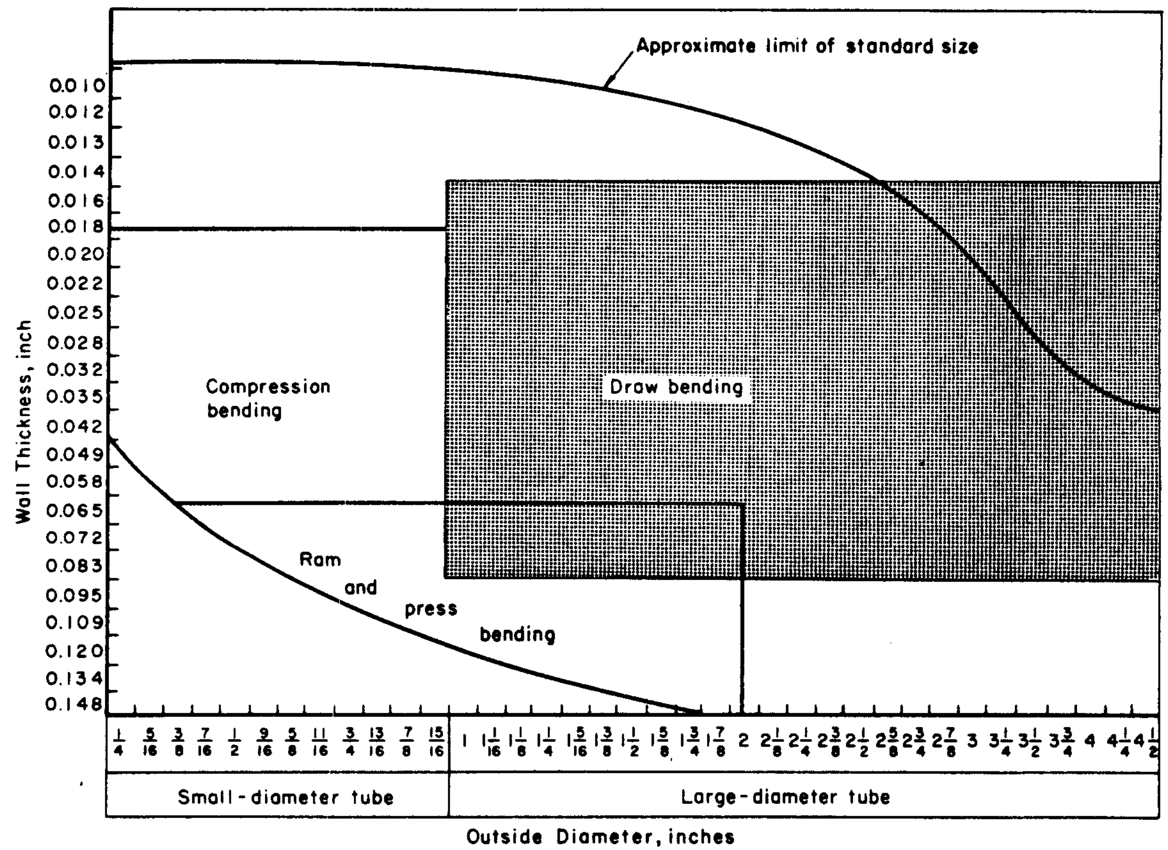


FIGURE 88. AREAS OF SUITABILITIES FOR VARIOUS BENDING PROCESSES BASED ON STANDARD TUBING SIZES OF STAINLESS STEEL (REF. 67)

Equipment. Nickel- and cobalt-base-alloy tubes are bent in commercially available equipment. The diameter of the tube dictates the equipment size. One equipment manufacturer* supplies aircraft, tube-bending equipment in the following sizes:

Bender Model No.	Maximum Tube Diameter, in.
3A	2-1/2
4	3 to 4
8A	4-1/2 to 6

Other producers of aircraft tube-bending equipment produce machines with similar capacities.

Tooling. SAE 4340 steel heat treated to Rockwell C 45-48 is adequate for the pressure die because it does not slide against the tube. The wiping die and mandrel that are subjected to sliding friction should be made from aluminum bronze (AMPCO 21).

Tube Preparation for Bending. Tubes straight within 0.030 inch per foot give good results and are normally purchased to that specification. Straightening tubes prior to bending can reduce the elongation limits of the material by as much as 20 per cent. Annealing after straightening or welding may cause problems if the tube warps during the annealing operation.

The diameters of the tubes to be bent must be held within +0.0025 to 0.007 inch, and the ovality should be within 6 per cent of the nominal tube diameter. These rather close tolerances are necessary to insure proper confinement of the tubes by the bending tools. Generally the tubes are cut to length with a trim allowance after forming.

Lubricants. Many conventional lubricants do not provide the continuous film needed to separate the tools from the workpieces under high bending loads. Ineffective lubrication causes galling. Drawing grease and oil have been used on stainless steel bending and should be suitable for bending nickel- or cobalt-base alloys.

Tube-Bending Precautions. If the mandrel body and balls, and the wiper die are allowed to wear down more than 0.005 to 0.008 inch, the tools will not confine the tubes adequately. Under such conditions pressure-die forces and the amount of elongation required to form the parts increase. This results in high failure rates.

*Pines Engineering Company, Inc., Aurora, Illinois.

Bending Limits. The bending limits depend mainly on the relationship of the bend radius to the tube diameter. The angle of the bend is not important for 90-degree or larger bends. The uniform elongation of the material is affected by the wall thickness of the tubing so that a decrease in formability in bending can be expected for tubing with a wall thickness of less than 0.035 inch.

The position of the neutral axis during bending influences the tensile strain in the outer tube fibers and the compressive strain in the inner tube fibers. Figure 89 shows the calculated tensile strain in the outer tube fibers when the neutral axis is located a distance of 1/2 and 1/3 D from the inner fibers of the tube. As shown in this figure the strain in the outer fibers decreases as the neutral axis moves away from the inside tube fibers for any given ratio of bend radius to tube diameter. Consequently, equipment that shifts the neutral axis away from the inner tube fibers during bending permits smaller bend radii to diameter ratios in a given material. The position of the neutral axis during rotary draw bending is usually between 1/3 D and 1/2 D. The exact position depends on the tooling and fit of the tubing on the tooling.

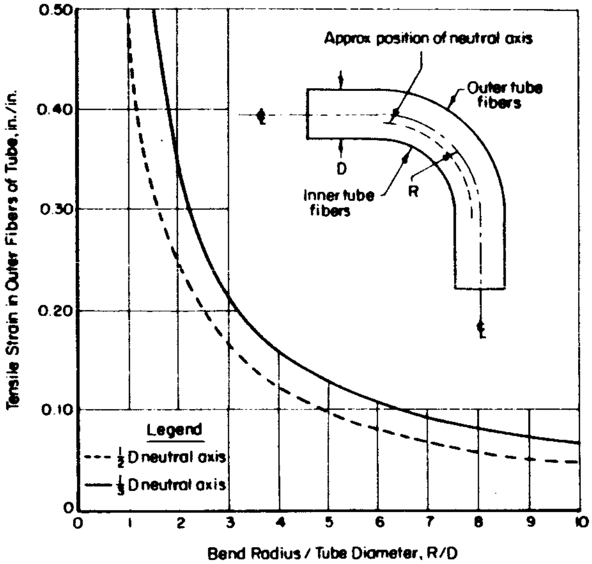


FIGURE 89. STRAIN IN THE OUTER TUBE FIBERS FOR A 90-DEGREE BEND WHEN THE NEUTRAL AXIS IS AT 1/3 D OR AT 1/2 D MEASURED FROM THE INNER TUBE WALL

Figure 89 may be used to determine the minimum ratio of bend radius to tube diameter for a given tube material and condition provided the tensile elongation value of the material at the same thickness as the tube is known. For example Inconel X-750 in the annealed condition has a tensile elongation of approximately 50 per cent. Tubing of this material could therefore be bent to a minimum ratio between 1 and 1-1/2 D depending on the position of the neutral axis in the bending procedure.

As the thickness of the tubing is decreased, the limiting factor in tube bending changes from elongation to compression stability. Buckling of thin sheet on the inner tube fibers becomes more of a problem as the thickness is decreased; this condition is accentuated by a shift of the neutral axis away from the inner tube fibers. The minimum bend-radii ratio should be increased by at least one number when the material thickness is 0.035 inch or less.

Post-Forming Operations. The tubing is generally trimmed to final length after forming where precise assembly work is required. The tubes are then cleaned to remove any lubricant or foreign material. For tubing that can be heat treated, the bending operation is generally carried out with the material in the solution-treated condition. The tubes are then aged after forming to obtain the final desired mechanical properties.

Tube Bulging.

Introduction. In bulging, an internal pressure is applied to form a tube to the desired shape. The internal pressure can be delivered by expanding a segmented punch or through a fluid, rubber, or other elastomer. The process, characterized by the use of simple and low-cost tooling, is adaptable to fast operations, and is capable of forming an acceptable part in one step. For most nickel- and cobalt-base alloys the process is limited to forming in the annealed or solution-treated conditions.

The two types of bulge forming can be classified as die forming and free forming. As the names imply, the die-formed component is made in a die that controls the final shape while the free-formed part takes the shape that will contain the internal pressure. Either type of operation can be carried out by a variety of processes.

Equipment Setup and Tooling. Conventional processes for bulge forming apply internal pressure to the tubing at a low rate by the motion of mechanical and hydraulic presses. A liquid or semiplastic filler material is normally used inside the tube as indicated in Figure 90, so that a hydrostatic pressure is approached.

The behavior of the filler material will control how closely hydrostatic conditions prevail during forming operations. When the ram, as shown in Figure 90, has been retracted, the rubber returns to its original diameter so that it may be withdrawn from the tube. This technique is commonly used because it does not present the sealing difficulties associated with the use of a liquid filler. The use of low-melting-point solids, such as Wood's Metal, as filler materials has shown promise for producing large deformations. In this process, the ram can apply axial force to the tube as well as pressure to the filler. If additional tubing material is fed into the die as the forming progresses, greater amounts of deformation are possible with this technique.

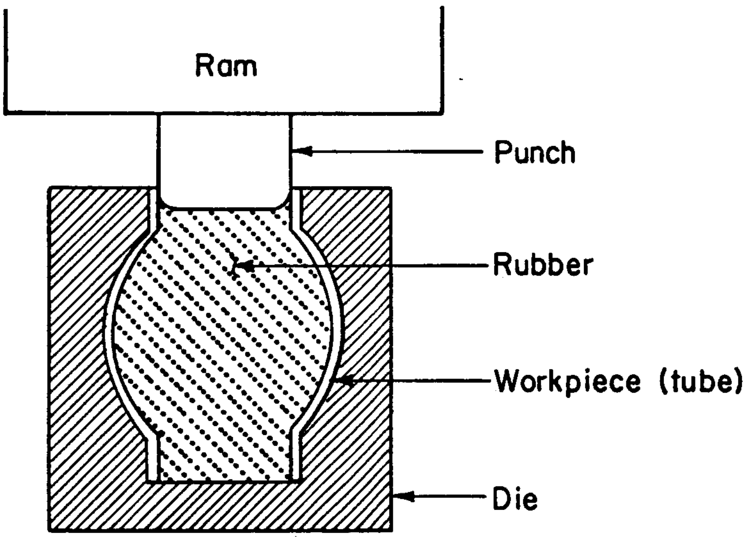


FIGURE 90. RUBBER-BULGING SETUP (REF. 25)

The use of expanding mandrels for bulging tubes is generally restricted to high-production applications because of the cost of the mandrels. Friction between the metal mandrel and the tubing limits the force that can be applied and the maximum deformation that can be obtained with this technique.

Some of the high-velocity techniques that have been applied to tube bulging with the greatest success employ low explosives and electric discharges as energy sources. The electric-discharge techniques are based on the liberation of energy stored in capacitors as sparks, exploding bridge wires, or magnetic coils. All of these processes except magnetic forming require some medium, generally water, to transmit the pressure to the tubing. The closed-die systems used to insure maximum efficiency complicate sealing. The volume between the tube and the die should be evacuated to prevent high temperatures and burning due to entrapped air. Shock-wave reflectors have been used with low-explosive and electrical-discharge systems to obtain unusual free-formed shapes. Most of the information on the subject, however, is considered proprietary and has not been released for general publication.

Magnetic forming is the only metalworking process that does not require direct contact between the forming medium and the workpiece. Consequently, the frictional limitations on forming encountered in most processes are absent.

If the pressure for deforming a tube is considered to be hydrostatic in nature, then the pressure required to initiate deformation can be determined from

$$P = 2TS/d \quad , \tag{22}$$

where

P = pressure, psi

T = tube-wall thickness, inches

S = the average flow stress of the tube material, psi

d = the tube diameter, inches.

This equation is simple to use for estimating pressure requirements at the start of deformation, but some modifications are required to present the total picture. As the tube is stretched, the flow stress will increase due to work hardening of the material. At the same time, the diameter increases and the thickness decreases. For estimates of the final or maximum pressure, the conditions prevailing after forming should be considered in the equation.

Material Preparation. Both seamless and welded nickel- and cobalt-base-alloy tubing is generally available in diameters from 0.012 to 4.5 inches and wall thicknesses from 0.004 to 0.148 inch. Larger size tubing has generally been made from roll-formed and welded sections. Some difficulty has been experienced in obtaining sufficient ductility in the heat-affected weld zone for bulge-forming operations. Some of the troubles may have been caused by improper manufacturing practices. It is normally desirable to planish weld beads before bulging and to stress relieve welded preforms.

Where considerable reduction in ductility is experienced in the weld heat-affected zone, a heavier section may be left in this area to equalize the strength of the tube. This technique, shown in Figure 91, will result in a part with uniform strength but may cause considerable difficulty in forming due to the reduced ductility in the heat-affected zone.

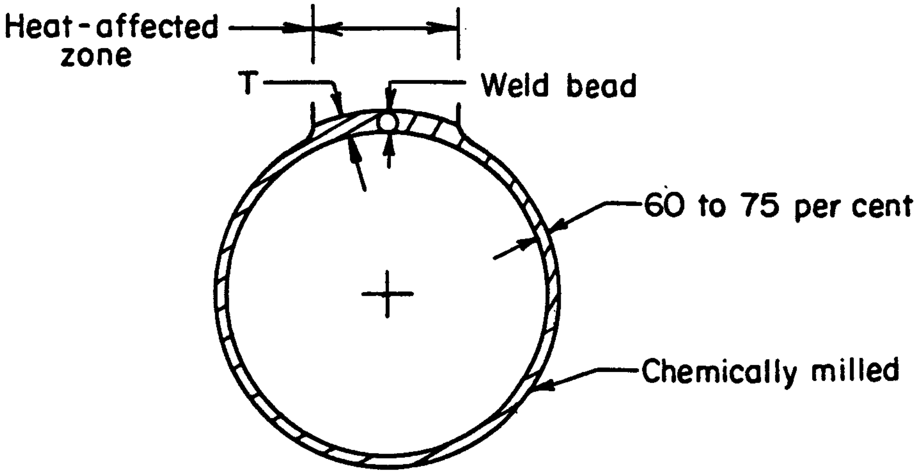


FIGURE 91. METHOD OF EQUALIZING STRENGTH BETWEEN WELD AND WALL AREAS FOR DIE-FORMED TUBES (REF. 26)

Bulge-Forming Limits. Two limitations must be considered in bulge-forming operations: ductility of the workpiece material and design of the tooling. The final part shape determines the maximum percentage increase in diameter. This can be calculated as follows:

$$\text{Percent Increase} = \frac{d_f - d_o}{d_o} \times 100 \quad , \tag{23}$$

where

d_o = the original diameter

d_f = the final diameter.

If no material is drawn in along the tube axis during forming, this may also be considered as the percentage stretch. The elongation values normally obtained in tensile tests cannot be used to determine this limitation since only uniform elongation is of practical importance. If necking occurs, as in the tensile test, the bulged component would be scrapped due to excessive metal thinning.

Tooling influences the amount of expansion because of the constraints it places on metal movement. If extra material is drawn in from the ends of the tubing or if the length of the tubing is shortened during forming, additional tube expansion is possible. The per cent increase in diameter can sometimes be increased by applying an axial load to the tube to assure feeding additional material to the bulged section.

Another limitation besides per cent stretch is the bending strain that occurs if the tube is made to bulge over too tight a bend radius. This condition results in splitting as shown in Figure 92. The minimum bend radii in tube forming should not be less than that used in other forming operations such as brake forming.

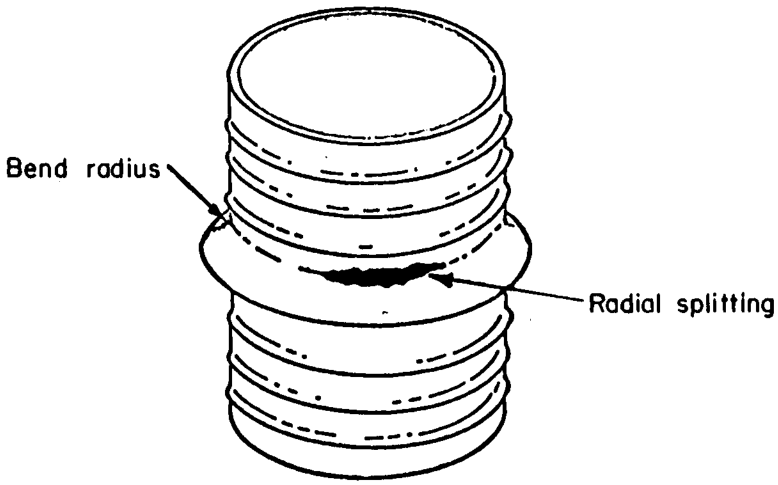


FIGURE 92. EXAMPLE OF FAILURE IN TUBE BULGING (REF. 26)

If the bulged portion of a tube is considered as a bead, the strain for any given die design can be determined. The important strains, on the basis of where failure will occur during bulge forming, are represented in Figure 93. The severity of deformation is determined by the amount of stretching and the amount of bending. Consequently, the radius at the entrance to the bulged areas as well as the diameter of the bulged section are both important considerations in establishing design limits in bulge forming. Figure 94 may be used to determine ϵ_A when the R_1/W ratio is known. The combined strain $\epsilon_A + \epsilon_{Br_1}$ determines failure limits so that the limiting bending conditions must be considered for the particular alloy of interest. This limit based on R_1/T or bend radius over material thickness is the same as for brake forming.

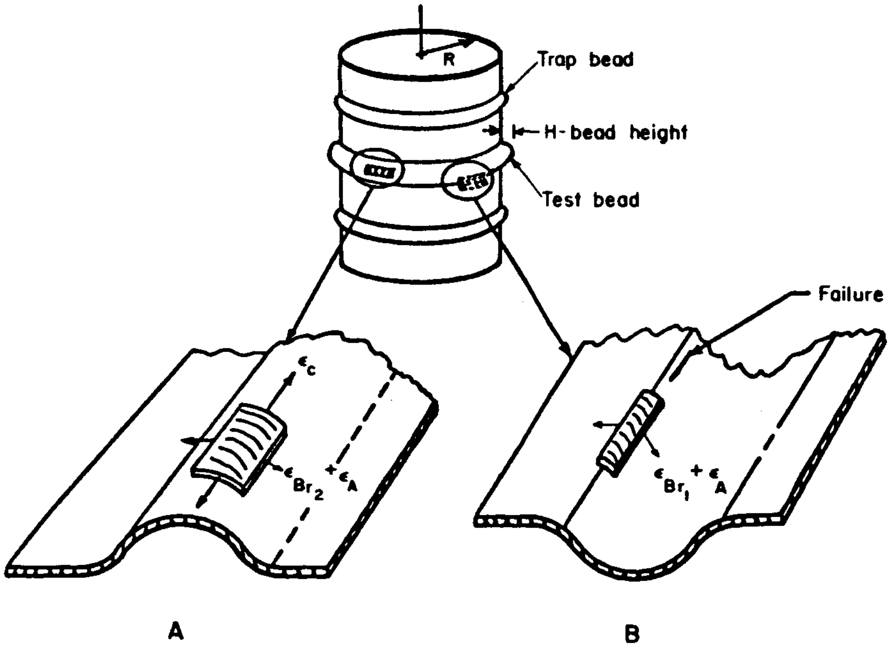


FIGURE 93. STRAIN CONDITIONS IN BULGE FORMING (REF. 26)

Figure 95 shows the limiting permissible amounts of stretching and bending strain for L-605 and René 41 in the annealed condition. The curves are based on tube-bulging experiments with 0.020 and 0.063-inch-thick material. Fracture would be expected to occur if attempts were made to bulge these materials to larger strains than those indicated by the trend lines. For example, the curves indicate that a part with a stretching strain of 0.2 in./in. should not be bent to a strain of more than 0.275 in./in. for René 41 or 0.35 in./in. for L-605. The end-forming limits are due to geometrical restraints.

When materials are to be deformed dynamically by one of the high-velocity techniques the uniform strain for the materials under this type of beading condition must be determined. Wood and associates (Ref. 26) have found that a maximum dynamic uniform strain, ϵ_u, correlates with the maximum axial or stretching strain, ϵ_A, in tube bulging. Thus, L-605 alloy has a maximum ϵ_u of 0.5 in./in. and an ϵ_A of 0.41 in./in., while René 41 has an ϵ_u of 0.42 in./in. and an ϵ_A of 0.36 in./in. The ϵ_A values can then be used in Figure 95 with the bending strain.

Care must be used in applying this technique to determine design limits for a particular material. The analysis is based on no axial

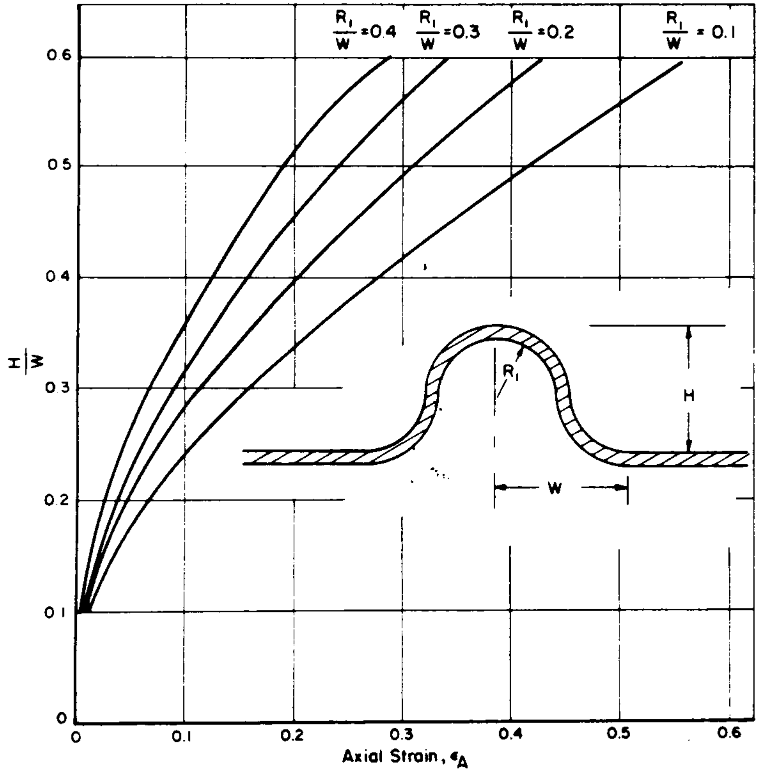


FIGURE 94. H/W VERSUS AXIAL STRAIN ϵ_A FOR VARIOUS VALUES OF R_1/W (REF. 26)

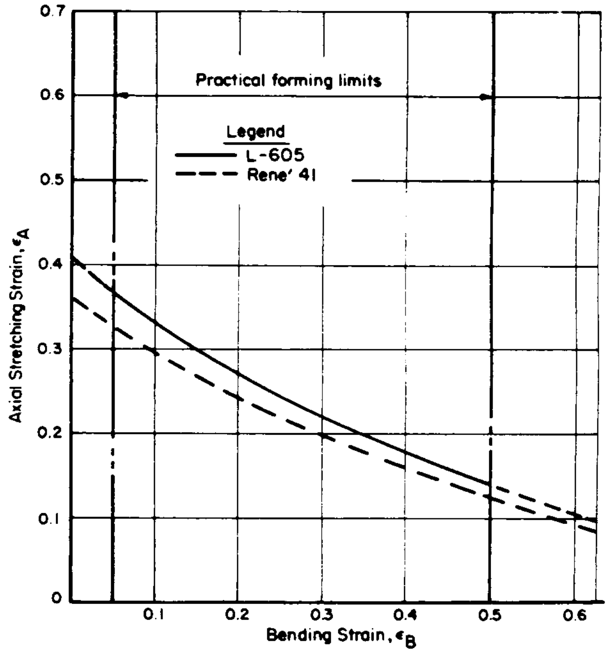


FIGURE 95. BENDING AND STRETCHING LIMITS FOR BULGE FORMING RENÉ 41 AND L-605 TUBING (REF. 26)

movement of material from the ends of the tube into the die. When such movement occurs, the axial strain will be less than that indicated. The analysis does not hold for eccentric-forming operations, which have a different strain pattern than that considered here.

Additional information on tube forming is required and should be obtained through development programs with the specific alloys to be used as tubing. In the absence of additional specific information, the only approach is to predict bulge-forming limits for tubing from data for uniform elongation and permissible bend radii obtained on sheet.

ROLL FORMING AND ROLL BENDING

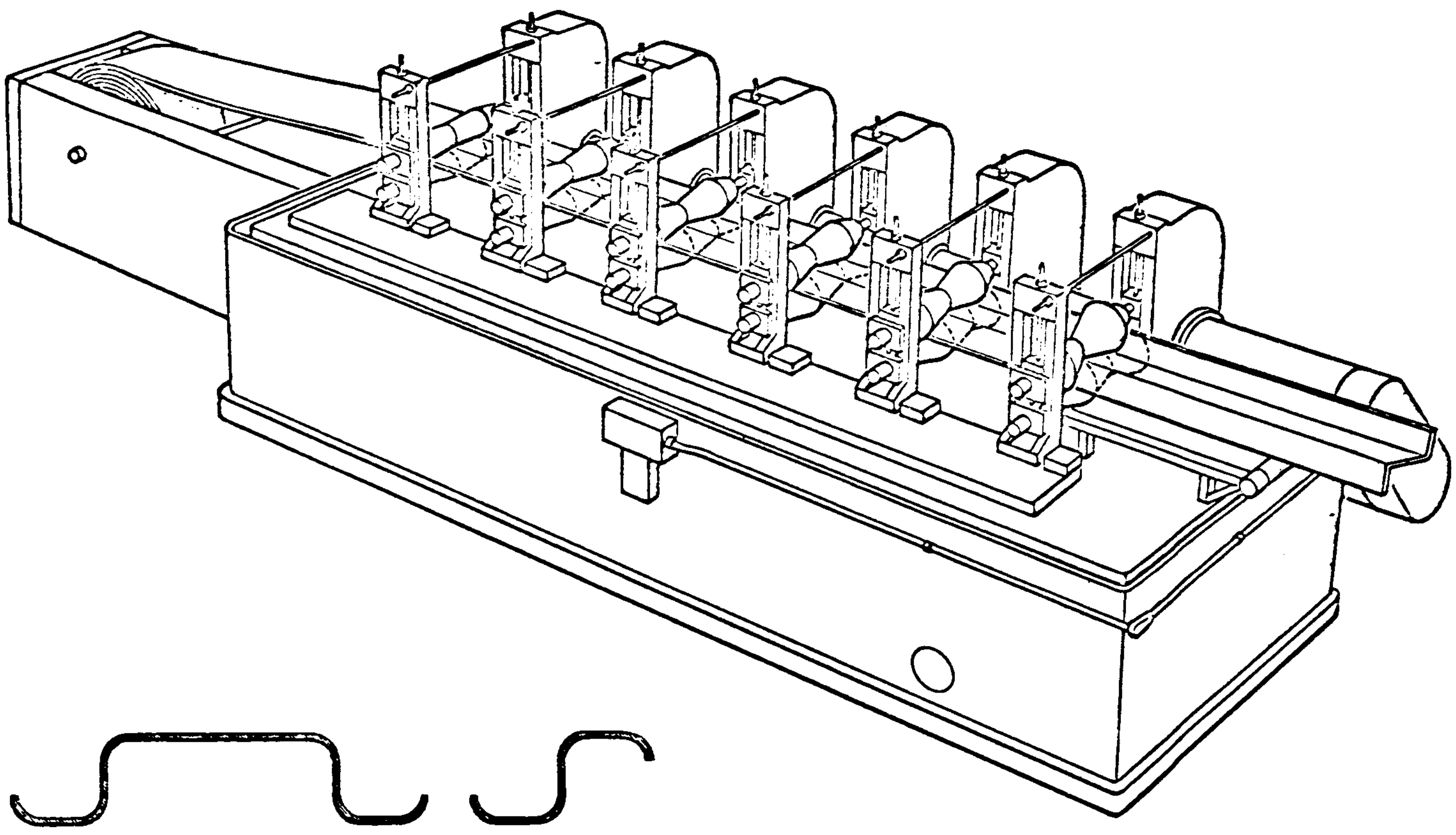
Introduction. This section of the report covers two types of secondary rolling operations used to change the shape of sheet or strip metal. They are:

(1) Forming by rolls whose contours determine the shape of the product. This process usually employs a sequence of power-driven rolls to produce long lengths of shaped products from sheet or strip.

(2) Bending between two or three cylindrical rolls that can be adjusted to curve sheet, bar, or shaped sections. With this technique, the length of sheet is controlled by the width of the rolls.

The term "roll forming" usually refers to a continuous bending process performed progressively by a series of contoured rolls in a special machine. With equipment of this kind (Figure 96), which can operate at speeds to 300 rpm, tolerances as small as ±0.005 inch can be obtained in cold forming. Roll forming is often used to bend strip into cylinders that are butt welded to produce thin-walled tubing with a relatively small diameter. The process is best suited to shapes made in large quantities.

Similar products can be made by draw-bench forming. This technique involves pulling the strip through a series of heads or stands containing undriven, or idling, rolls. Both methods, roll forming and draw-bench forming, are used to form the nickel- and cobalt-base alloys into structural hat sections, angles, "T" sections, and channels. Normally these operations are performed at room temperature.



Typical Sections

FIGURE 96. SCHEMATIC DRAWING OF ROLL-FORMING MACHINE

Courtesy of North American Aviation, Inc.,
Los Angeles, California.

Roll bending is often used to bend sheet into cylindrical, single-contour shapes that can later be welded to form tube or pipe of rather large diameters. Aircraft producers and fabricators have roll-bending facilities that are capable of contouring flat sheets into cylinders up to about 36 feet long. Facilities capable of bending structural shapes by means of rolls are available and frequently used to produce large-radius bends in channels and other sections. Such sections may be used to support skins in aircraft manufacturing.

Roll Forming. Relatively little, if any, information is available in the technical literature on the roll forming of the nickel- and cobalt-base alloys. The process is a large production technique not well suited to producing small quantities of a single shape. When only small quantities are required, other forming methods or combinations of methods are used for which equipment is on hand. Such alternative forming methods might include brake bending, trapped-rubber forming, bench forming, and the like.

One application is known in which Inconel strip is fabricated into 3/8 to 1/2-inch-diameter tubing using a combination procedure involving both roll forming and automatic welding. Usually six or seven roll passes are required to produce the tubing from strip and an extra step is then utilized to butt weld the rolled tubing. Such automatic equipment also incorporates sizing of the tubing, flash trimming, and cutting off into desired lengths in an uninterrupted operation. Figure 97 is a photograph of an automatic tube line that carries out the above-named steps.

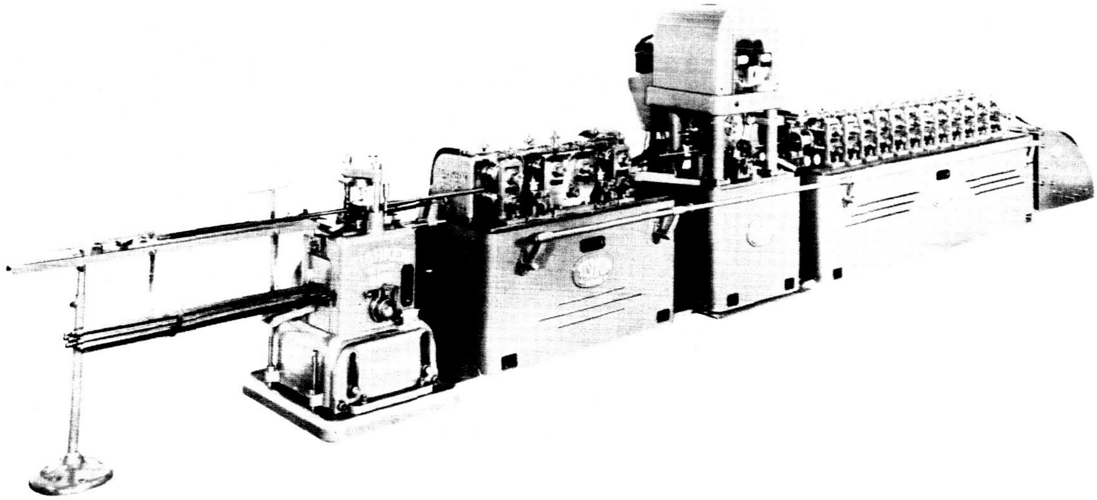


FIGURE 97. A PRODUCTION LINE TO PRODUCE WELDED TUBING
Courtesy of Tishkin Products Company, Detroit, Michigan.

Roll Bending. Roll bending is an economical process for producing single-contoured skins from sheet materials. In addition to bending flat sheet into cylindrical contours, the linear-roll-bending technique also is commonly used to curve heel-in and heel-out channel sections. The channels initially may have been produced by roll forming on a press brake, or even by extrusion. In addition to roll bending, the final contour of a channel or other section also might be produced by stretch-forming techniques. Curved angle sections may be produced by bending channel sections to the desired contour and then splitting the channels to form the angle sections.

Figure 98 is a sketch of a typical setup for the linear roll bending of channels (Ref. 33). The upper roll in the pyramid-type-roll configuration can be adjusted vertically as shown in the figure, and the radius of the bend is controlled by the adjustment of this roll. The geometry for heel-in and heel-out channels also is shown in the sketch.

Roll bending is a process that depends greatly on operator technique. Premature failures will occur if the contour radius, R, is decreased in increments that are too severe. On the other hand, too many passes through the rolls may cause excessive work hardening in the channel. An operator usually must form several trial parts of a new material in order to establish suitable conditions.

Equipment. Linear-roll-bending equipment generally is quite simple in design. One common type of equipment utilizes a pyramidal design both in vertical and horizontal machines. Three rolls are used, two lower rolls of the same diameter placed on fixed centers at the same elevation, and a third or upper roll placed above and between the lower rolls. The upper roll may be adjusted vertically to produce different curvatures and all three rolls are driven. Figure 99 shows a vertical roll bender of the type used by Wood, et al. (Ref. 33) in their study of linear roll bending of channels. Such equipment also can be used for making helical coils from angles and channels, flat sections edgewise, and pipes, by changing the rolls to the appropriate design.

Another type of equipment for bending shapes is the pinch-type roll bender, so called because its two main rolls actually pinch the stock between them with sufficient pressure to pull the material through against the resistance of the bending stress. This equipment contains four rolls, as shown in Figure 100. The upper and lower main rolls are driven by a train of gears, and the lower roll, directly beneath the upper one, is adjustable vertically. The large rolls

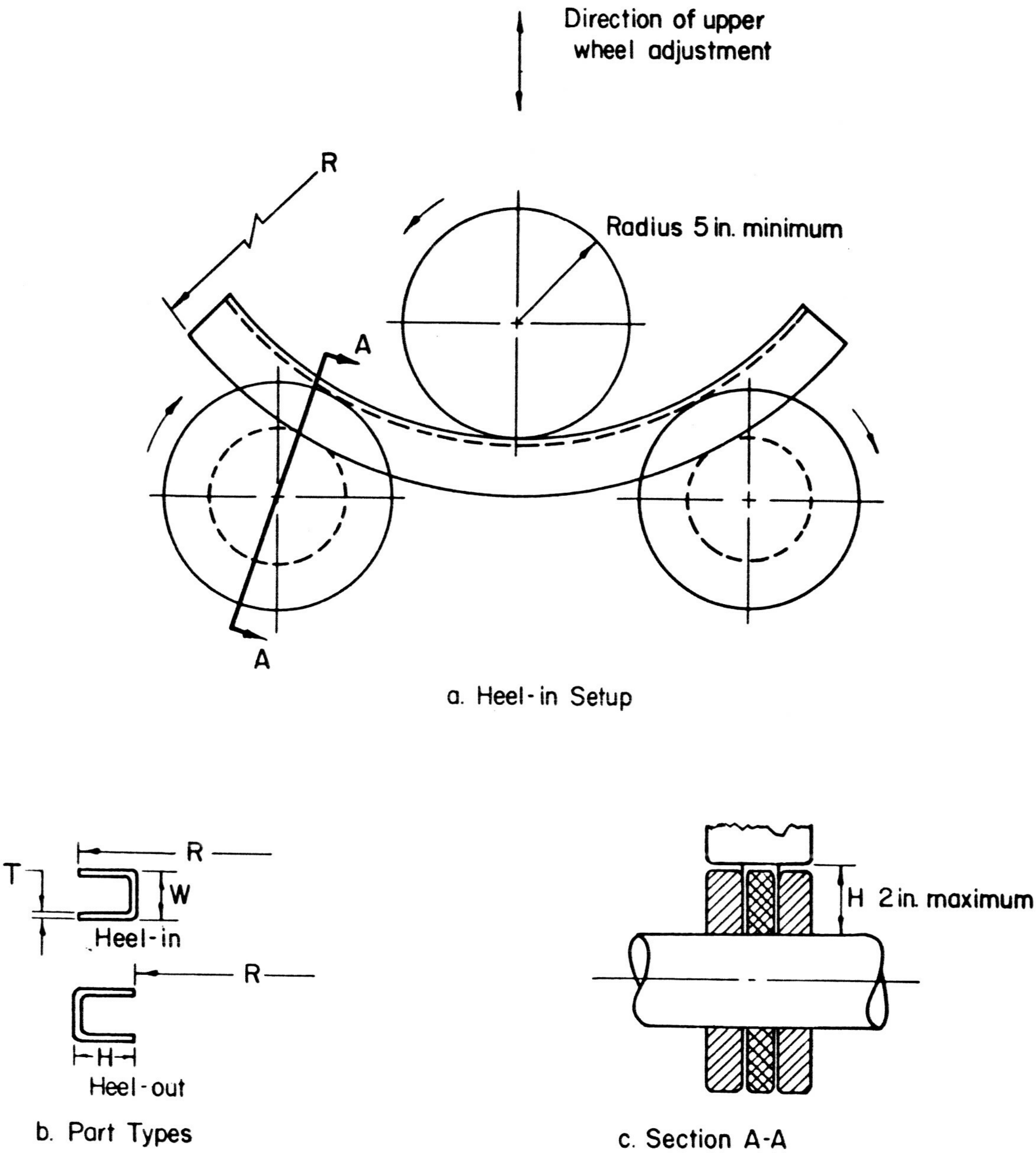


FIGURE 98. PART TYPES AND SETUP FOR ROLL BENDING (REF. 33)

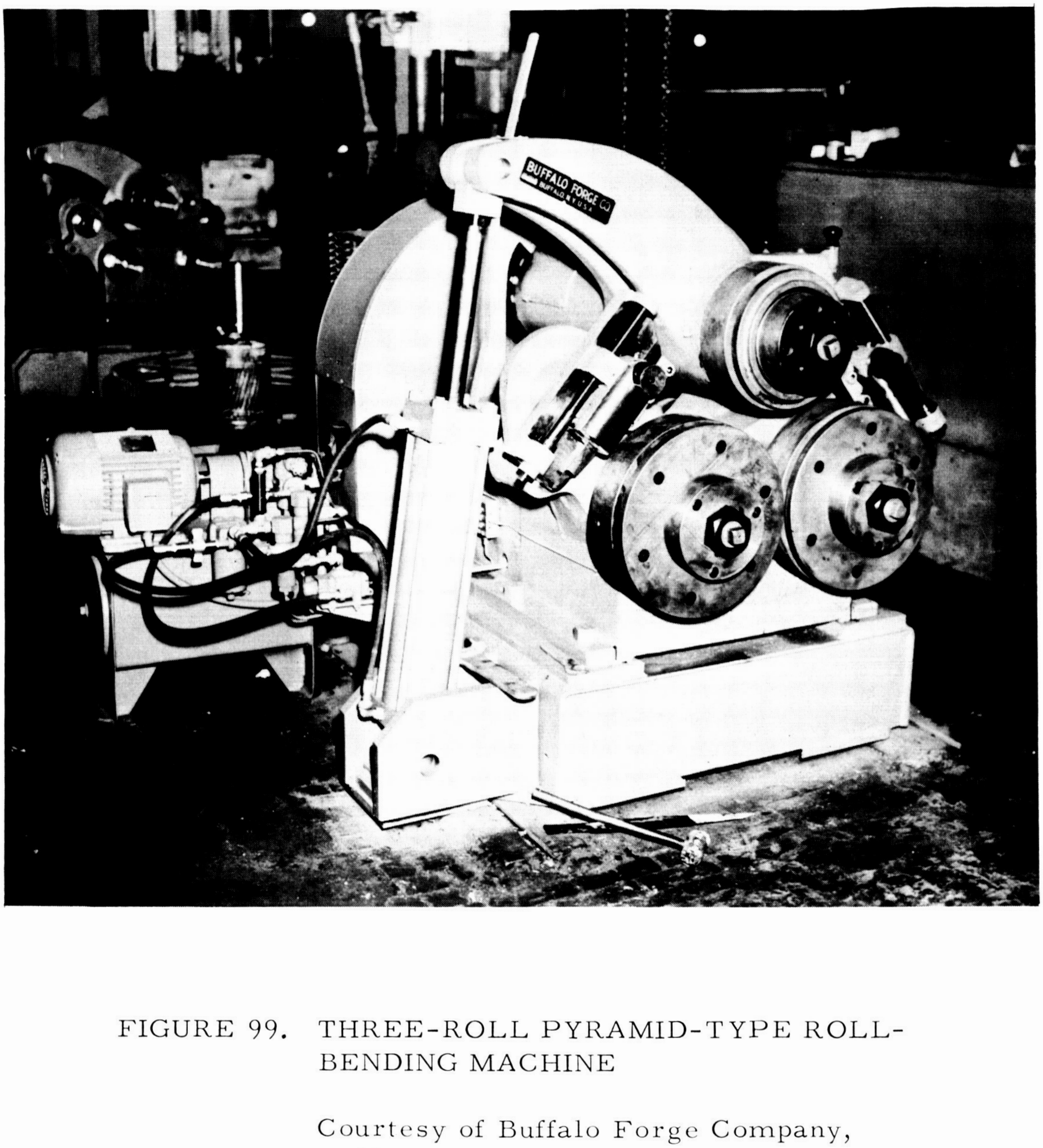


FIGURE 99. THREE-ROLL PYRAMID-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York.

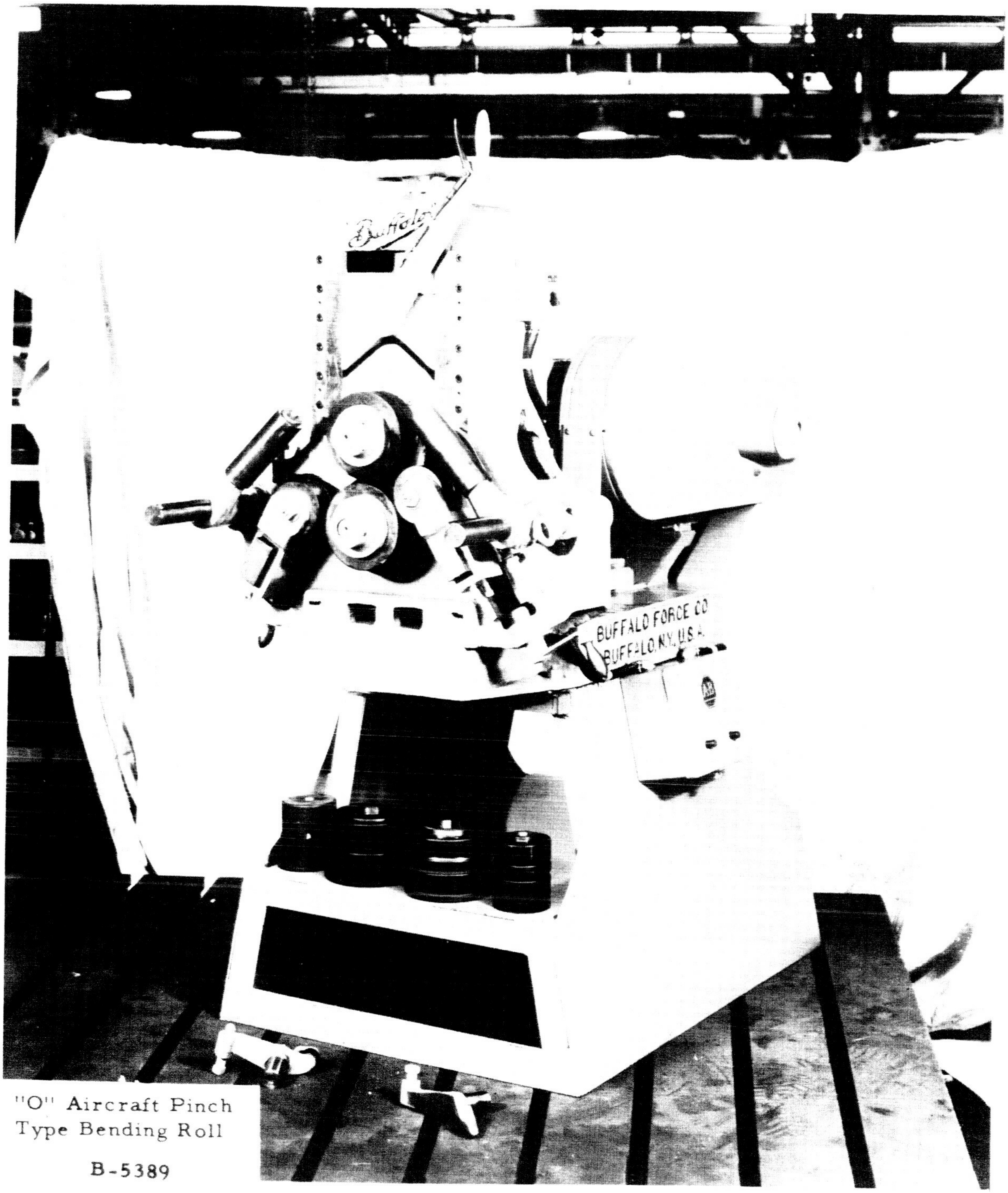


FIGURE 100. CONFIGURATION OF ROLLS IN AIRCRAFT PINCH-TYPE ROLL-BENDING MACHINE

Courtesy of Buffalo Forge Company, Buffalo, New York.

support the flanges of the shape during bending and tend to minimize buckling by supporting the sides of the flanges. The small idler rolls can be adjusted up and down, as shown in Figure 100, for changing the bend radius.

Table XXVIII gives information on a number of roll-bending machines produced by one manufacturer. The punch-type machines have smaller capacities than the pyramid-type rolls and are largely used for relatively light aircraft parts.

In addition to rolls for contouring channels and other shapes, equipment also is available for bending sheet sections into shapes. Figure 101 is a view of the roll-bending equipment at the Columbus Division of North American Aviation. Three bending rolls of varying size are shown, the largest of which is about 15 feet long and the smallest about 4 feet long. The equipment is used to bend such aircraft parts as wing-leading edges, doors, aircraft skins, etc. Table XXIX gives data on the sizes and other characteristics of sheet-bending rolls produced by one manufacturer. One characteristic of this type of equipment is that the diameter of the rolls is rather small, frequently being of the order of 1-1/2 to 2 inches. The rolls are backed up, as can be seen in Figure 101, by a series of smaller rollers to prevent bending deflections during rolling.

Another type of roll-bending equipment is made specifically for producing cylindrical and other closed sections from sheet. Such equipment is called a slip-roll former or bender, and these machines feature pinch-type rolls. They are very versatile and adaptable to many operations. The equipment uses larger diameter rolls than the sheet-forming rolls just described and is characterized by the ability of the upper roll to swing open at one end (outboard bearing) to permit easy removal of the completed cylinder or other closed shape without distortion. Table XXX gives data on the sizes and other pertinent characteristics of these slip-roll-bending machines.

Tooling. Rolls for linear contour bending of shapes have been made from a variety of materials. Sometimes the rolls are made from hard rubber or beryllium copper for use at room temperature with relatively soft materials or for short runs with harder alloys. Rolls on roll-bending machines are commonly made from tool steels. These may range from Grades O-2 for room-temperature application to Grades H-11 and H-13 for elevated-temperature use. Rolls for the sheet-roll-bending machines, such as are shown in Figure 101, may also be made of low-alloy steels such as Grade 4130

TABLE XXVIII. PERTINENT DATA ON ROLL-BENDING MACHINES PRODUCED BY ONE MANUFACTURER[a]

	Vertical Bending			Vertical Pinch	
Model No.	1/2	1	2	00	0
Centers Lower Rolls	8	12	18	--	--
Diameter Angle Rolls, in.	7	11-3/8	16-1/2	3-1/4	5-1/4
Rolls, rpm	18	11.2	7	72.5	40
Feet per Minute	33	34	31	65	60
Motor Size, hp	5	10	20	1-1/2	2
Motor Speed, rpm	1800	1800	1,800	1800	1800
Diameter, Upper Shaft, in.	3	4-3/4	6	1-5/8[b]	2-1/2[b]
Diameter, Lower Shaft, in.	2-1/2	4	5	1-5/8	2-1/2
Gear Ratio	97	156	250	24	45
Length, in.	47	61	82	34	42
Width, in.	60	62	78	30	36
Height, in.	41	58	65	34	50
Weight With Motor, lb	2300	6300	13,200	875	1175
		<u>Capacities (Typical)</u>			
Angles, Leg-Out, in.	2 x 2 x 1/4	3 x 3 x 3/8	4 x 4 x 5/8	7/8 x 7/8 x 1/8	1-1/2 x 1-1/2 x 3/16
Minimum Diameter, in.	20	24	40	20	24
Angles, Leg-In, in.	1-1/2 x 1-1/2 x 1/4	2-1/2 x 2-1/2 x 3/8	3-1/2 x 3-1/2 x 5/8	3/4 x 3/4 x 1/8	1-1/4 x 1-1/4 x 3/16
Minimum Diameter, in.	18	30	48	30	48
Smallest Angle, Leg-Out, in.	3/4 x 3/4 x 1/8	1-1/2 x 1-1/2 x 3/16	1-1/2 x 1-1/2 x 1/4	1/2 x 1/2 x 1/8	1/2 x 1/2 x 1/8
Minimum Diameter, in.	8	13	18	4	6
Smallest Angle, Leg-In, in.	3/4 x 3/4 x 1/8	1-1/2 x 1-1/2 x 3/16	2 x 2 x 1/4	1/2 x 1/2 x 1/8	1/2 x 1/2 x 1/8
Minimum Diameter, in.	9	14	24	6	7
Channels, Heel-In, in.	3 - 4#	5 - 11-1/2#	9 - 20#	--	--
Channels, Heel-Out, in.	--	5 - 9#	7 - 14-3/4#	--	--
Minimum Diameter, in.	16	18	48	--	--

(a) Data taken from Bulletins 326/F and 352/G of the Buffalo Forge Company, Buffalo, New York.
(b) At roll.

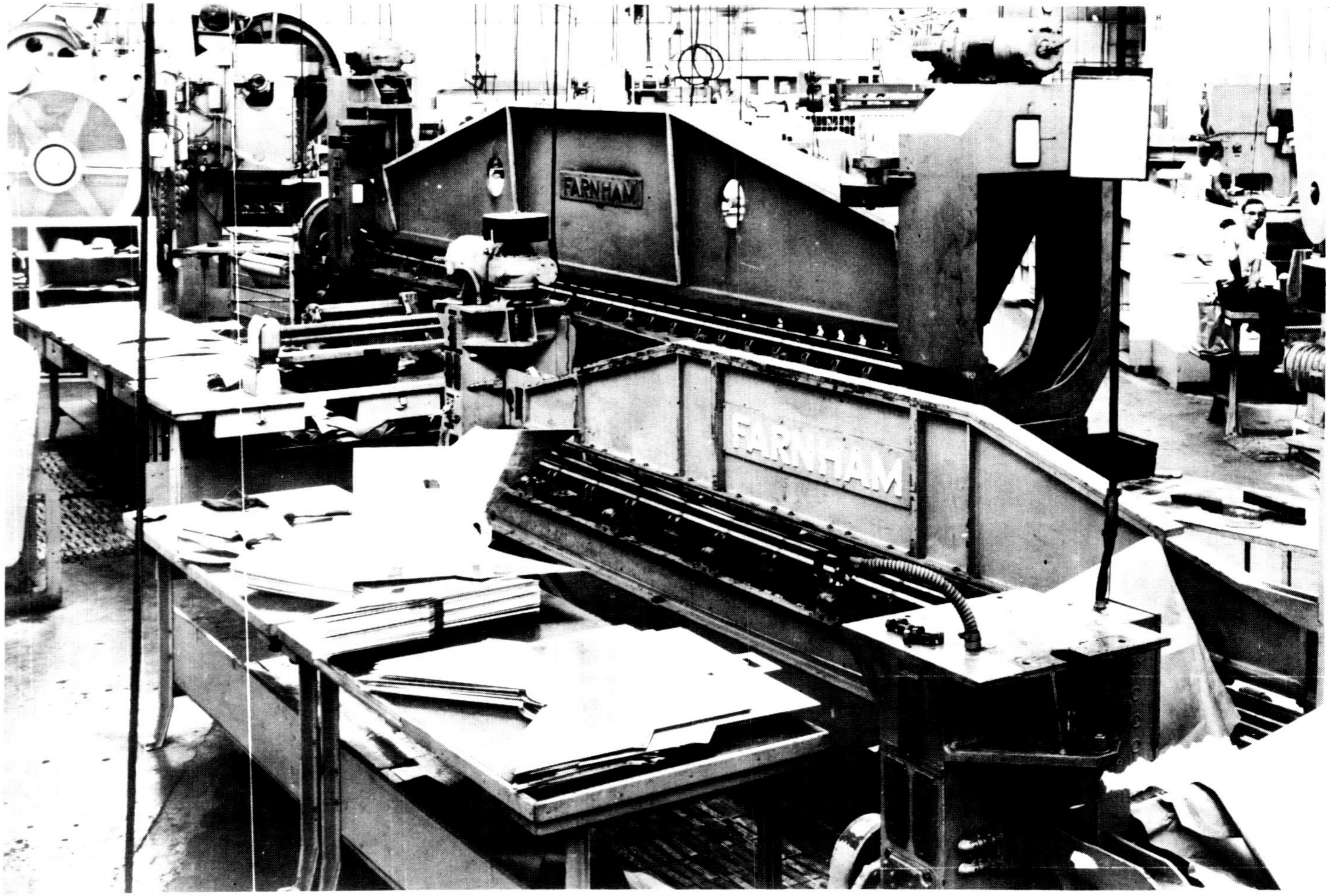


FIGURE 101. THREE SIZES OF SHEET-ROLL-BENDING EQUIPMENT RANGING IN CAPACITY FROM 4 TO 15 FEET

Courtesy of Columbus Division, North American Aviation, Inc.

TABLE XXIX. COMPILATION OF DATA ON SHEET-FORMING ROLLS PRODUCED BY ONE MANUFACTURER[(a)]

Model No.	Useable Length of Rolls, ft	Minimum Bend Radius, in.	Maximum Material Thickness (Tensile Strength <60, 000 psi), in.	Approximate Weight, lb	Dimensions, ft Overall Length	Dimensions, ft Height
			Model E			
658-E	6	5/8	0.063	4,300	11-5/12	7-1/3
610-E	8	1	0.063	4,400	11-5/12	
858-E	8	5/8	0.063	5,035	13-5/12	7-1/3
1058-E	10	5/8	0.063	5,765	15-1/3	7-1/3
1258-E	12	5/8	0.063	6,500	17-1/3	7-1/3
1558-E	15	5/8	0.063	7,300	20-1/3	7-1/3
1510-E	15	1	0.063	7,550	20-1/3	7-1/3
1810-E	18	1	0.063	8,500	23-1/3	7-1/3
			Model EX			
1010-EX	10	1	0.094	6,900	16-1/12	8-1/3
1210-EX	12	1	0.094	7,740	18-1/12	8-1/3
1510-EX	15	1	0.094	9,000	21-5/6	8-5/6
2015-EX	20	1-1/2	0.094	21,000	26-1/2	9-2/3
2410-EX	24	1	0.094	32,700	33-1/2	9-3/4
			Model EXX			
610-EXX	6	1	0.125	5,150	12-1/12	8-1/3
810-EXX	8	1	0.125	6,800	14-1/12	8-1/3
1010-EXX	10	1	0.125	8,450	16-5/6	8-1/3
1210-EXX	12	1	0.125	10,100	18-5/6	8-1/3
1515-EXX	15	1-1/2	0.125	23,400	22-1/4	9-1/2
2015-EXX	20	1-1/2	0.125	26,000	27-1/4	9-3/4
			Model EXXX			
1015-EXXX	10	1-1/2	0.190	15,775	18-3/4	9
1215-EXXX	12	1-1/2	0.190	19,635	20-3/4	9-1/3
1515-EXXX	15	1-1/2	0.190	25,400	23-5/6	9-3/4
1615-EXXX	16	1-1/2	0.190	26,450	25-1/6	9-3/4
2015-EXXX	20	1-1/2	0.190	30,600	28-5/6	9-3/4
			Model H4X			
606-H4X	6	6	0.250	22,000	16	9
806-H4X	8	6	0.250	25,000	18	9
1006-H4X	10	6	0.250	28,000	21	10
1206-H4X	12	6	0.250	31,000	23	10
1506-H4X	15	6	0.250	35,400	26-1/12	10-3/4
1606-H4X	16	6	0.250	37,300	27-1/12	10-3/4
1806-H4X	18	6	0.250	40,000	29-1/2	10-3/4
2006-H4X	20	6	0.250	42,500	31-1/2	10-3/4
2406-H4X	24	6	0.250	47,500	35-1/2	10-3/4

(a) Data taken from Booklet 1-58 from Farnham Division, The Wiesner-Rapp Co., Inc., Buffalo 10, New York.

TABLE XXX. SUMMARY OF SLIP-ROLL-BENDING MACHINES PRODUCED BY ONE MANUFACTURER[a]

Model No.	Model Lengths	Range of Rated Capacity, Mild Steel, Sheet Thickness, in. or gage	Range of Working, Length of Rolls		Diameter of Rolls, in.	Speed of Rolls, fpm	Approximate Range of Shipping Weight, pounds	
			Longest, in.	Shortest, in.			Longest	Shortest
1-1/2-1	2	24 to 30 gage	20	16	1 or 1-1/2	(b)	85	40
2	6	16 to 24 gage	42	12	2	18[c]	405	270
3	3	14 to 18 gage	48	36	3	22[c]	920	850
4	4	10 to 18 gage	72	36	4	15[c]	2, 235	1, 960
5	5	3/16 in. to 16 gage	96	36	5	25	4, 320	2, 750
6	4	5/16 in. to 12 gage	120	48	6	25	8, 665	4, 950
9	6	5/8 in. to 10 gage	168	48	9	16	19, 725	10, 725
10	6	3/4 in. to 3/16 in.	168	48	10	18	20, 450	10, 950

(a) Based on data in Booklet 203C and Bulletin 77H from Niagara Machine and Tool Works, Buffalo, New York.
(b) Hand operated.
(c) Available also as hand-operated machines.

with flame-hardened surfaces. The surfaces usually have a Rockwell C hardness of about 50.

Lubricants. Lubricants are almost always required for the roll forming of nickel- and cobalt-base alloys because these alloys tend to gall. For roll forming at room temperature, fluids such as SAE 60 oil, castor oil, lard oil, sperm oil, and mixtures of mineral oil and water function both as lubricants and coolants. When the forming forces are high, lubricants with higher viscosities give best results. Solid lubricants are often used for roll forming at elevated temperatures. The lubricants may be applied by spraying, dipping, brushing, or wiping.

Linear-Roll-Bending Limits for Channels. Transverse buckling and wrinkling, respectively, are the common modes of failure in bending heel-out and heel-in channels. Basic equations for predicting the bending behavior of channels of various alloys in linear roll bending were developed by Wood and his associates (Ref. 33). The principal parameters, shown in Figure 102, are the bend radius, R, the channel height, H, the web width, W, and the material thickness, T. The following three equations were developed for heel-in channel to construct a formability curve of the type shown in Figure 102.

The equation for the inflection line is

$$\frac{H}{R} = 0.0146 \left(\frac{H}{T}\right)^{1/2} \quad . \tag{24}$$

The equation for the elastic buckling line below the inflection line is

$$\frac{H}{R} = \frac{E_t}{S_{ty}} \left[\frac{0.025}{\left(\frac{H}{T}\right)^2}\right] . \tag{25}$$

The equation for the buckling line above the inflection line is

$$\frac{H}{T} = \left[1.713 \frac{E_t}{S_{ty}}\right]^{2/5} \quad . \tag{26}$$

Similar equations were developed for the linear roll bending of heel-out channels.

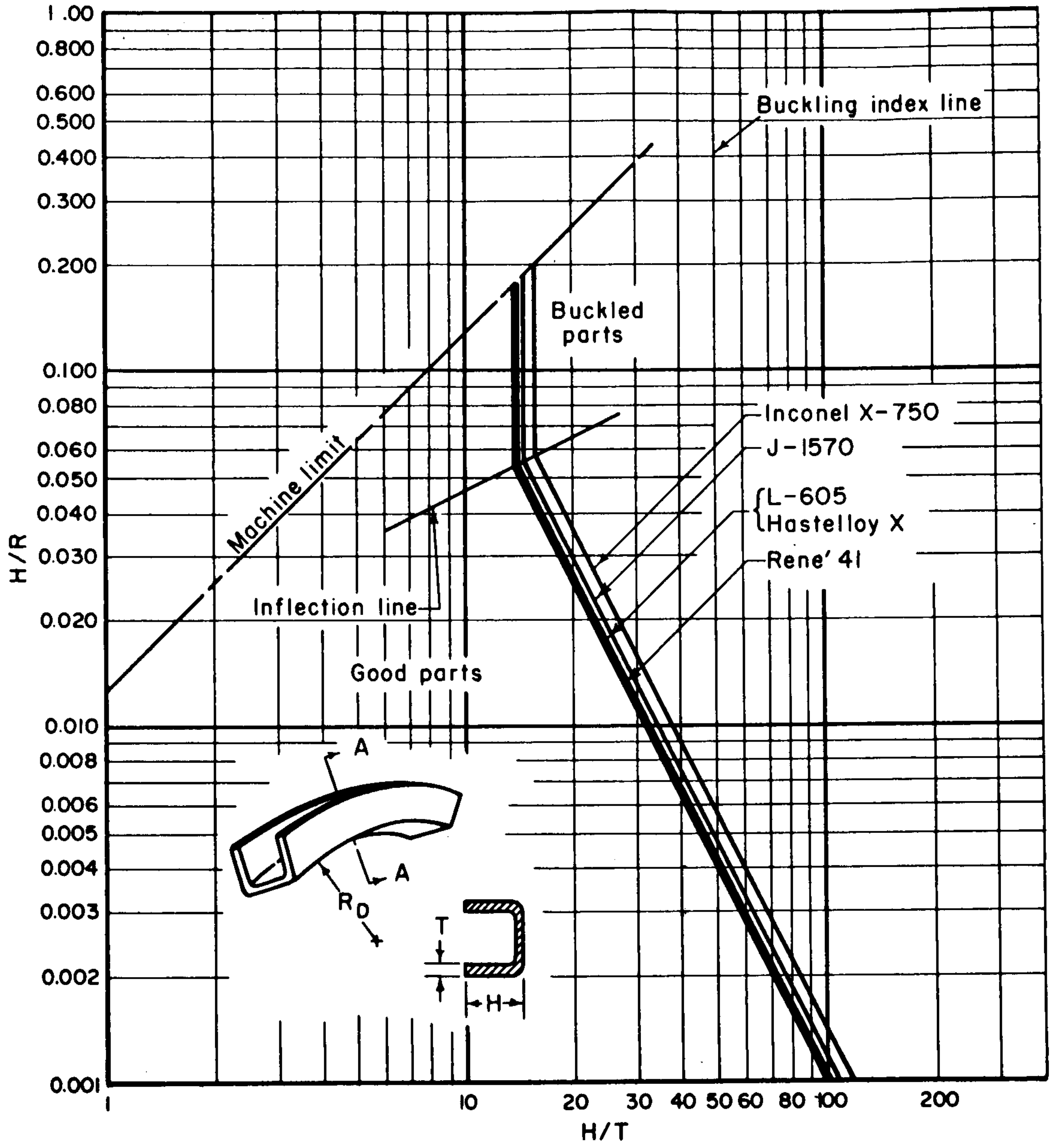


FIGURE 102. LINEAR-ROLL-BENDING LIMITS FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS (HEEL-IN CHANNELS) (REF. 33)

The equation for the inflection line is

$$\frac{H}{R} = 0.0209 \left(\frac{H}{T}\right)^{1/2} \quad . \tag{27}$$

The equation for elastic buckling below the inflection line is

$$\frac{H}{R} = \frac{E_c}{S_{cy}} \left[\frac{0.02116}{\left(\frac{H}{T}\right)^2} \right] \quad . \tag{28}$$

The equation for buckling above the inflection line is

$$\frac{H}{T} = \left[1.01 \, \frac{E_c}{S_{cy}} \right]^{2/5} \quad . \tag{29}$$

The formability curve for heel-out channels is shown in Figure 103.

In addition to the values defined above, the following values also are required to solve these equations:

E_t and E_c = moduli of elasticity in tension and compression, respectively. These values are very nearly equal for practical purposes.

S_{ty} = tensile yield strength.

S_{cy} = compressive yield strength.

The tensile yield strength is a characteristic of sheet that is commonly measured to define the strength of the sheet. Room-temperature values of tensile yield strength and elastic modulus found in the literature are listed in Table XXXI. These values may be used to calculate the E/S_{ty} and E/S_{cy} ratios required to solve Equations (25), (26), (28), and (29). It is here assumed that the compressive yield strengths, S_{cy}, required for Equations (28) and (29), will not differ significantly from the tensile yield strengths given so that the values given may be used for both cases.

The compressive yield strength is a property that commonly is not determined for sheet materials. However, ASTM standards have been agreed upon for performing this test both at room and elevated temperature. Although the elastic modulus in compression is generally slightly higher than that in tension, it usually is considered to be equal for all practical purposes.

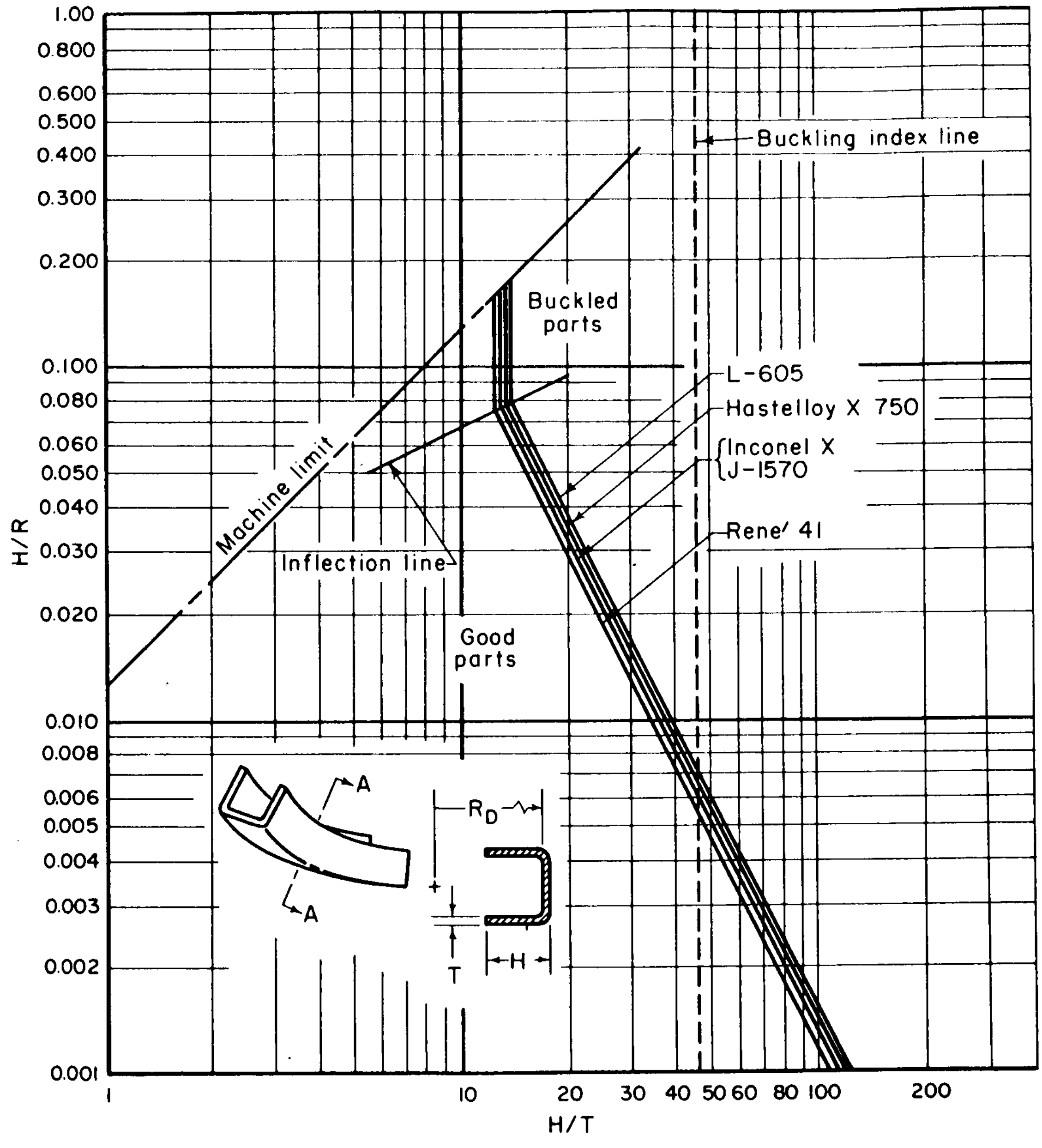


FIGURE 103. LINEAR-ROLL-BENDING LIMITS FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS (HEEL-OUT CHANNELS) (REF. 33)

TABLE XXXI. TYPICAL ROOM-TEMPERATURE VALUES OF YOUNG'S MODULUS OF ELASTICITY AND TENSILE YIELD STRENGTHS FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS[a]

Alloy	Condition	E x 10^6, psi	Tensile-Yield Strength, S_{ty}, ksi	E/S_{ty}
		Nickel-Base Alloys		
Nickel 200	Annealed	30.0	21.5	1393
Nickel 211	"	30.0	35.0	867
Nickel 230	"	30.0	20.0	1500
Monel 400	"	26.0	30.0	866
Monel K500	Hot rolled	26.0	49.0	531
Inconel 600	Annealed	31.0	36.5	850
Inconel 721	"	31.0	45.0	688
Inconel 722	Aged	31.0	99.0	313
Inconel X-750	Solution treated	31.0	60.0	517
Inconel 751	Annealed	31.0	75.0	413
Incoloy 825	"	28.0	35.1	797
Hastelloy B	Rolled	26.5	50.0	530
Hastelloy C	"	29.8	58.0	514
Hastelloy F	"	29.0	45.0	644
Hastelloy X	Annealed	28.6	52.0	550
Waspaloy	Solution heat treated	30.5	93.0	328
	Aged	35.0	106.0	330
R-235	(c)	30.0	88.0	341
Nimonic 75	Annealed	27.0	55.0	491
Nimonic 90	"	31.0	90.0	344
Rene 41	"	31.6	74.2-88.2[b]	425-358
		Cobalt-Base Alloys		
Hastelloy 25	(c)	35.0	65.0	538
Refractory 80	(c)	34.0	102.0	333
J-1570	(c)	33.5	134.0[d]	250
J-1670	(c)	34.1	148.0	230
S-816	(c)	35.0	72.0	486
Nivco-10	(c)	29.7	110.0	270
L-605	Solution treated	34.2	57.5	595

(a) Much of data taken from Tables 2 and 4.
(b) 74.2 ksi for 0.025-inch-thick sheet; 88.2 ksi for 0.063-inch-thick sheet.
(c) Condition not stated but presumed to be solution treated and aged.
(d) Properties at 1200 F.

In addition to the limitation on the production of suitable roll-bent parts by both buckling and splitting of the channel, another limiting parameter is the mechanical limit of the bending machine. This limit depends on the thickness of the material, the maximum section height that the tooling will accommodate, and the minimum part radius that the machine and tooling will produce. If any of these variables are changed, the position of the machine limit line also will be changed. Needless to day, the use of other roll-bending equipment will change the position of the machine limit line and also of the buckling limit line of the alloy. Therefore, it should be emphasized that roll-bending limits derived by Wood, et al., are probably valid only when used with a pyramid-type, three-roll-bending machine. The added support provided by pinch-type rolls probably would move the buckling limit line to the right.

Figures 102 and 103 give limits for the linear roll bending of heel-in and heel-out channels, respectively, for three nickel-base and two cobalt-base alloys, as treated by Wood, et al. (Ref. 33). All five of the alloys show similar behavior although René 41 is the most difficult of these alloys to form by linear roll bending by only a slight amount.

The data in Figures 102 and 103 can also be presented in tabular form (Refs. 33,36). Tables XXXII and XXXIII give roll-forming limits for heel-in and heel-out channels, respectively. These data can be used as follows:

(1) Calculate $R_{D/T}$ ratio from given dimensions

(2) Compare the $R_{D/T}$ ratio with the critical $R_{D/T}$ ratio given in the table

(a) If the calculated $R_{D/T}$ ratio is less than the critical ratio, the part cannot be formed due to machine limitations. This is based on the capacity of a Kane-Roach three-roll machine used to determine the values in the table.

(b) If the calculated $R_{D/T}$ ratio is greater than the critical $R_{D/T}$ ratio in the table, interpolate the tabular $R_{D/T}$ ratios and corresponding H/T values for buckling to determine the required H/T ratio. Multiply H/T by the material thickness, T, to determine the maximum flange height, H_{max}.

TABLE XXXII. LINEAR-ROLL-BUCKLING LIMITS (HEEL-IN CHANNELS) (REF. 25)

Material	Critical Ratio, R_D/T		Buckling Limits, H/T, for H/R Ratios of						
			0.001	0.005	0.010	0.020	0.030	0.040	0.050
Hastelloy X	60	H/T	102	46	33	23	10	16	15
		R_D/T	101,898	9,154	3,267	1,127	615	384	284
Inconel X-750	60	H/T	117	53	38	26	22	19	17
		R_D/T	116,883	10,547	3,762	1,274	712	456	323
René 41	60	H/T	99	44	32	22	18	16	14
		R_D/T	98,901	8,756	3,168	1,078	582	384	266
J-1570	60	H/T	107	48	34	24	20	17	15
		R_D/T	106,893	9,552	3,366	1,176	647	408	284
L-605	60	H/T	102	46	33	23	19	16	15
		R_D/T	101,898	9,154	3,267	1,127	615	384	284

TABLE XXXIII. LINEAR-ROLL-BUCKLING LIMITS (HEEL-OUT CHANNELS) (REF. 25)

Material	Critical Ratio, R_D/T		Buckling Limits, H/T, for H/R Ratios of							
			0.001	0.005	0.010	0.020	0.030	0.040	0.050	0.060
Hastelloy X	86	H/T	115	52	38	26	21	19	17	15
		R_D/T	115,115	10,452	3,838	1,326	721	494	357	265
Inconel X-750	86	H/T	110	50	36	25	20	18	16	15
		R_D/T	110,110	10,050	3,636	1,275	687	468	336	267
René 41	86	H/T	105	48	34	28	20	17	15	14
		R_D/T	105,105	9,648	3,434	1,428	687	442	315	247
J-1570	86	H/T	110	50	36	25	20	18	16	15
		R_D/T	110,110	10,050	3,636	1,275	687	468	336	257
L-605	86	H/T	120	54	39	27	22	19	17	16
		R_D/T	120,120	10,854	3,939	1,377	756	494	357	283

Example 1 (Ref. 36). Determine the maximum flange height for roll forming a channel of 0.125-in.-thick Inconel X-750 nickel-base superalloy to a 7-in. heel-in counter radius (use Table XXXII).

R_D = 7 in.; T = 0.125 in.; $R_{D/T}$ = 7/0.125 = 56, which is less than the critical $R_{D/T}$ (60).

Therefore, it is impossible to form the part due to machine limitations.

Example 2 (Ref. 36). Determine the maximum flange height for roll forming a channel of 0.020-inch-thick J-1570 cobalt-base superalloy to a 12-inch heel-out contour radius (use Table XXXIII).

R_D = 12 inches; T = 0.020 inch; $R_{D/T}$ = 12/0.020 = 600, which is greater than critical $R_{D/T}$ (86). For $R_{D/T}$ = 687, H/T = 20, and for $R_{D/T}$ = 468, H/T = 18. Interpolating for $R_{D/T}$ = 600, H/T = 19.21 H_{max} = H/T x T = 19.21 x 0.020 = 0.384 inch.

Graphs similar to Figures 102 and 103 and tables similar to Tables XXXII and XXXIII can be constructed from experimental values of E/S_{ty} and E/S_{cy} for the alloys of interest.

Roll Bending of Sheet. Sheet of nickel- and cobalt-base alloys have been contoured by rolling, but no systematic study, such as that conducted by Wood, et al., for the roll bending of channels, has been reported. For successful roll bending of sheet, the sheet must be flat within 0.6 per cent.

The roll-bending equipment for contouring sheet is rated on the bending of mild steel or of aluminum alloy. The yield strength of mild steel is about 50,000 psi, that of aluminum alloys about 73,000 psi, and that of some of the nickel- and cobalt-base alloys may range from about 21,000 to nearly 150,000 psi depending on the alloy and the condition of heat treatment.

The capacity of a given sheet-roll-bending machine can usually be estimated on the basis of the square of the thickness of sheet being formed. Thus, if a given piece of equipment is capable of bending 1/4-inch-thick aluminum plate (73,000 psi yield), it probably would have only the capacity to bend about 0.222-inch-thick annealed Waspaloy (93,000 psi). This rule of thumb is useful in preventing overloading of bending rolls. The above assumes that the cylinder lengths of the two materials are equal. Conversely, if the two materials in the above example were of the same thickness, then the stronger Waspaloy sheet would have to be about 20 per cent shorter.

Figure 104 shows an Inconel 600 bell retort fabricated by welding together a series of roll-bent plates and a domed top. Many similar applications of roll-bent nickel- and cobalt-base parts joined by welding can be found in industry, especially in applications where the good corrosion and/or high-temperature properties of these materials are beneficial. These applications might include tanks for storing and/or hauling corrosive chemicals, tanks to resist pitting and corrosions from brines used in food processing, retorts and similar furnace parts, external sections on some missile and aircraft including the X-15 experimental airplane, and the like.

DIMPLING

Introduction. Dimpling is a process for producing a small conical flange around a hole in sheet-metal parts that are to be assembled with flush or flat-headed rivets. The process is often used for preparing fastener holes in airframe components because the flush surface reduces air fraction. Dimpling is most commonly applied to sheets that are too thin for countersinking. Since drilled holes have smoother edges than punched holes, they are more suitable for dimpling. Sheets are always dimpled in the condition in which they are to be used because subsequent heat treatment may cause distortion and misalignment of holes.

Principles. Figure 105 is a sketch of the dimpled area in a sheet. As would be expected in a press-die-forming operation of this kind, the permissible deformation depends on the ductility of the sheet. The amount of stretching required to form a dimple, e, varies with the head diameter, D, of the fastener, the rivet diameter, 2R, and the bend angle, α, according to the relationship (Ref. 44):

$$e = \left(\frac{D}{2R} - 1\right)\left(1 - \cos\alpha\right) . \qquad (30)$$

If the ductility of the material is insufficient to withstand forming to the intended shape, cracks will occur radially in the edge of the stretch flange or circumferentially at the bend radius, as is shown in Figure 106. The latter type of failure is more prevalent in thinner sheet. Radial cracks are more common in thick stock.

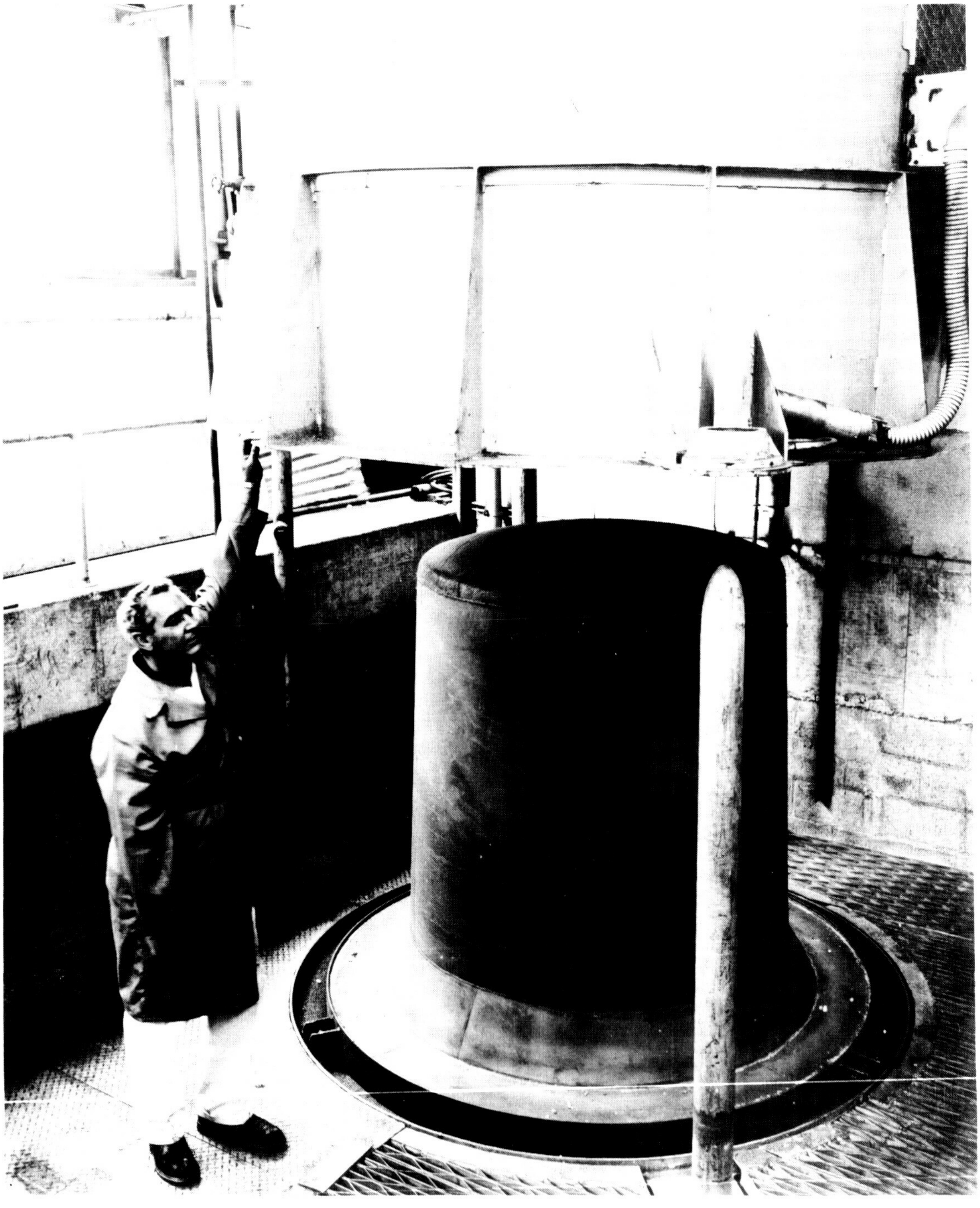


FIGURE 104. INCONEL BELL-FURNACE RETORT FABRICATED IN SECTIONS BY SHEET-ROLL BENDING AND THEN WELDED TOGETHER

Courtesy of California Alloy Products, Los Angeles, California.

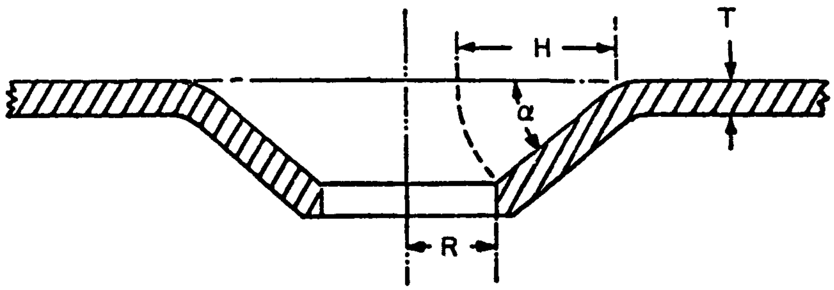


FIGURE 105. PARAMETERS FOR DIMPLING (REF. 33)

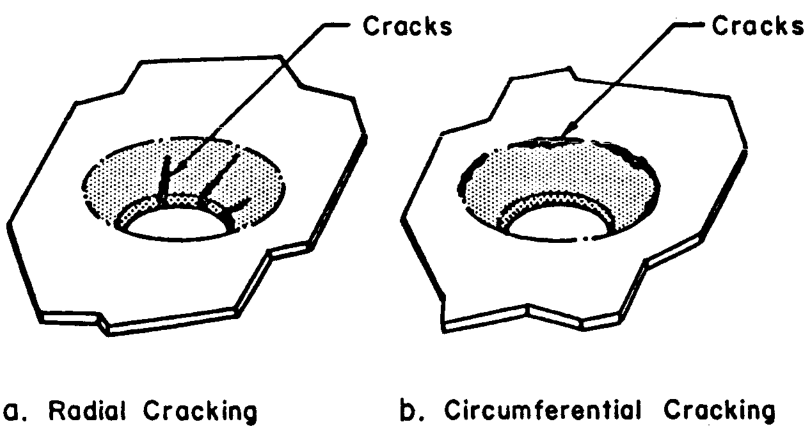


FIGURE 106. MAJOR FAILURES IN DIMPLING (REF. 25)

The general equation developed by Wood and his associates (Ref. 33) for predicting dimpling limits from the parameters indicated in Figure 105 is:

$$\frac{H}{R} = \frac{0.444\ (\epsilon_{2.0})^{0.253}}{1 - \cos\alpha} \quad . \tag{31}$$

The value $\epsilon_{2.0}$ in the equation is the elongation in a two-inch gage length for the material and temperature of interest (e.g., $\epsilon_{2.0} = 0.5$ for 50 per cent elongation).

The standard dimple angle, α, in Figure 105, is 40 degrees although other angles may be used for special purposes. Dimpling requires a considerable amount of ductility and many of the nickel- and cobalt-base alloys are sufficiently ductile to be dimpled at room temperatures. Consequently, elevated temperatures may be required to dimple only some of the stronger and less ductile materials. The ram-coining-dimpling process is most common although dimples have been produced at room temperatures by swaging. The essential features of the ram-coin-dimpling operation are indicated in Figure 107. In this process a pressure in excess of that required for forming is applied to coin the dimpled area and reduce the amount of springback.

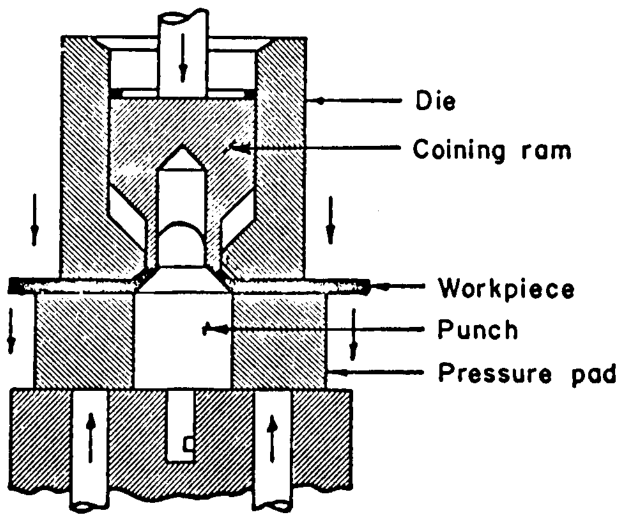


FIGURE 107. CROSS SECTION OF RAM-COIN DIMPLING (REF. 25)

Equipment. The choice of the size of ram-coining-dimpling equipment depends on the pressures needed to deform the sheet. A guide in choosing size ranges for dimpling machines needed to produce dimples for various rivet and screw sizes is tabulated on the following page (Ref. 68).

Size	Pressure Capacity, lb
3/32 to 1/8-inch rivets	Up to 10,000
5/32-inch rivet	10,000 - 20,000
3/16-inch rivet and screw	15,000 - 25,000
1/4-inch rivet and screw	18,000 - 40,000
5/16-inch screw	25,000 and up

The capacities of four commercially available dimplers are given in Table XXXIV. A photograph of the Chicago Pneumatic CP 450EA Dimpling Machine Frame equipped with a hot, triple-action, ram-coin-die unit is shown in Figure 108. A competitive machine in which the dies are heated by induction coils is shown in Figure 109.

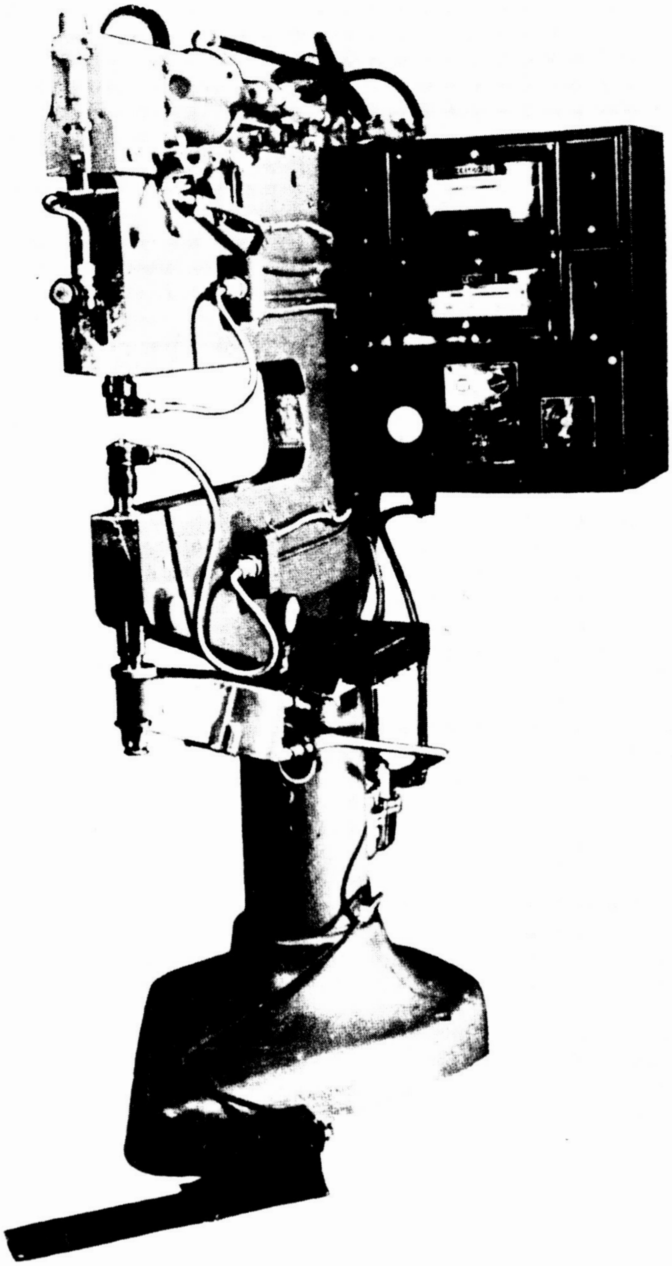
TABLE XXXIV. CAPACITIES AVAILABLE IN COMMERCIALLY AVAILABLE DIMPLING MACHINES (REF. 68)

Model No.	Dimpling Pressure Capacity, lb	Manufacturer
CP450EA	20,000	Chicago Pneumatic Tool Co.
AT256S	30,000	Aircraft Tools Company
CP640EA	40,000	Chicago Pneumatic Tool Co.
AT260A	100,000	Aircraft Tools Company

Tooling. A typical sequence of operations for dimpling is shown in Figure 110. The five positions shown for a triple-action ram-coin-dimpling machine are the approach, preform, coining, end of stroke, and retraction.

Some nickel- and cobalt-base alloys must be dimpled at elevated temperatures. The practical optimum-temperature limit is 1200 F, which is about the highest temperature at which tool steels may be used as die materials. If dimpling must be done at higher temperatures, the use of high-strength, high-temperature alloys or ceramic-tooling materials is required to prevent deformation of the die materials during dimpling.

Elevated-temperature dimpling is usually done with heated dies. The sheet to be dimpled may be heated by contact with the heated dies, as shown in Figure 111. Conduction-heated, ram-coin tooling may be used for temperatures up to 1000 F. Resistance-heated dimpling equipment is used for higher temperatures. The tooling that is heated by resistance in one application is shown in Figure 112.



Left-side view showing triple-action controls

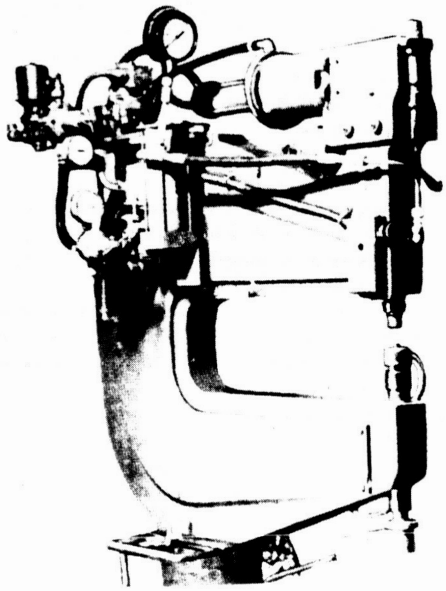


FIGURE 108. CP450EA HOT, TRIPLE-ACTION RAM-COIN DIMPLER

Fully automatic with electric and pneumatic controls.

Courtesy of Zephyr Manufacturing Company, Inglewood, California.

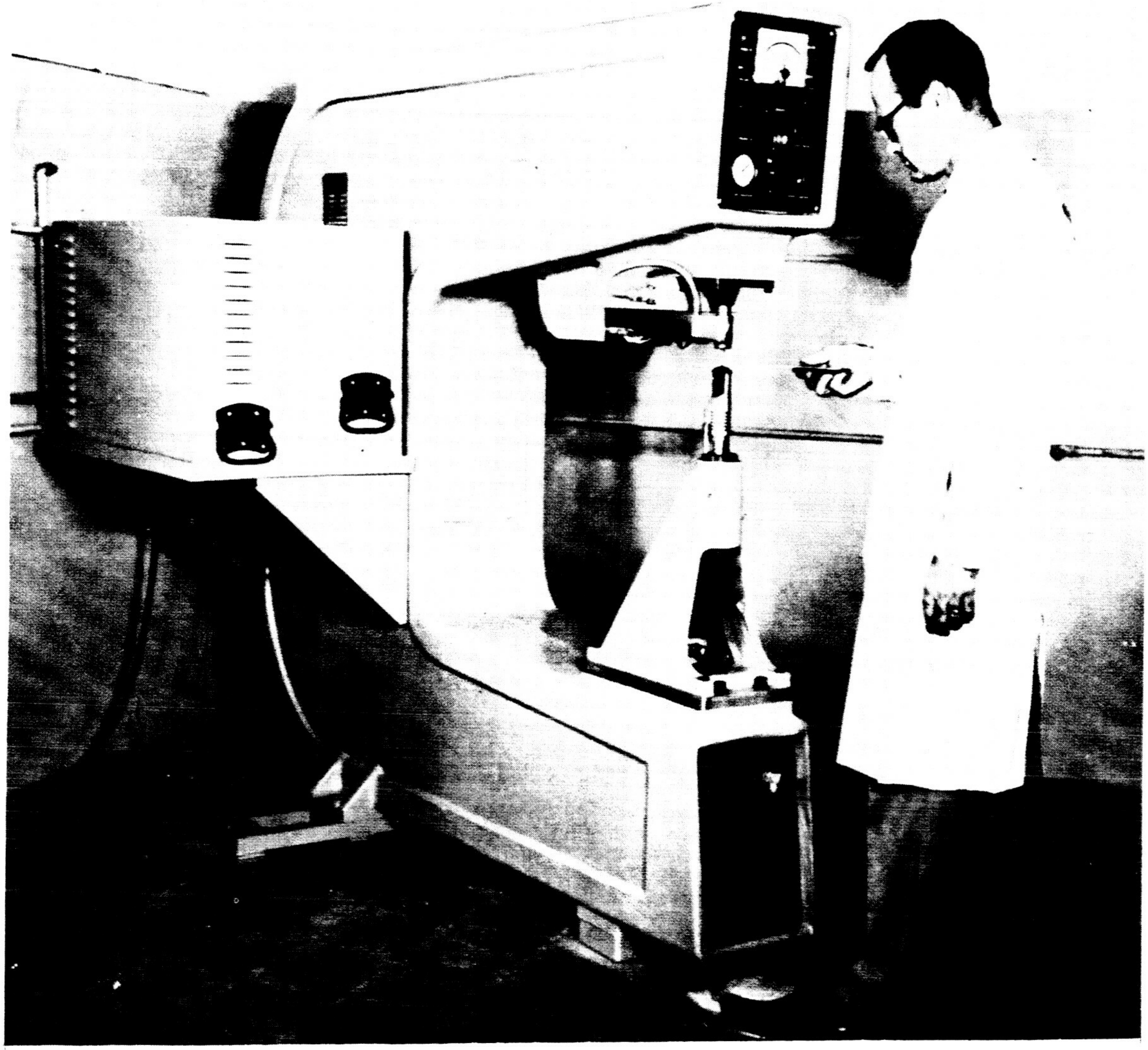


FIGURE 109. INDUCTION-COIN-DIMPLING MACHINE

Courtesy of Aircraft Tools, Inc., Los Angeles, California.

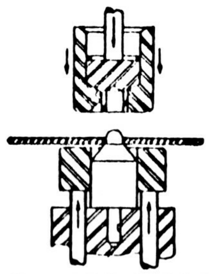
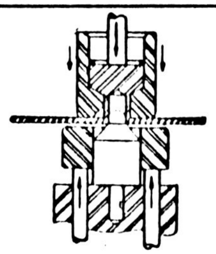
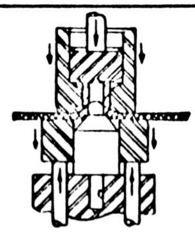
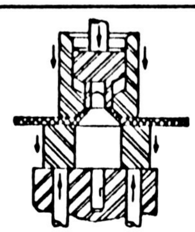
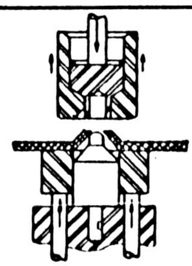
Position 1		**a. Approach** Sheet is positioned, with punch pilot in pilot hole and die assembly is coming down to contact position; loading force on coining ram is at preselected value
Position 2		**b. Preform** Die assembly has just contacted work, and timed heating stage is beginning; controlled preforming pressure is increasing to partially form dimple and to further accelerate heat transfer
Position 3		**c. Coining** Timed "Preform" stage has ended, and final coining stage begun; downward movement of die assembly is creating firm gripping action between die and pad faces in area around dimple, preventing outward flow of material as dimple is coined; coining ram controls hole stretch and balances internal strains, eliminating radial and internal shear cracks
Position 4		**d. End of Stroke** Dimple is now fully formed; the confining action of pad face, die face, and coining ram has forced material into exact conformation with tool geometry
Position 5		**e. Retraction** As die assembly retracts to starting position, load on pressure pad raises pressure pad to starting position and strips dimple from punch cone **f. Result** Minimum sheet stretch, minimum hole stretch, maximum definition, improved nesting

FIGURE 110. SEQUENCE OF OPERATIONS IN TRIPLE-ACTION RAM-COIN DIMPLING AT ELEVATED TEMPERATURE

Courtesy of Convair, General Dynamics Corporation, San Diego, California.

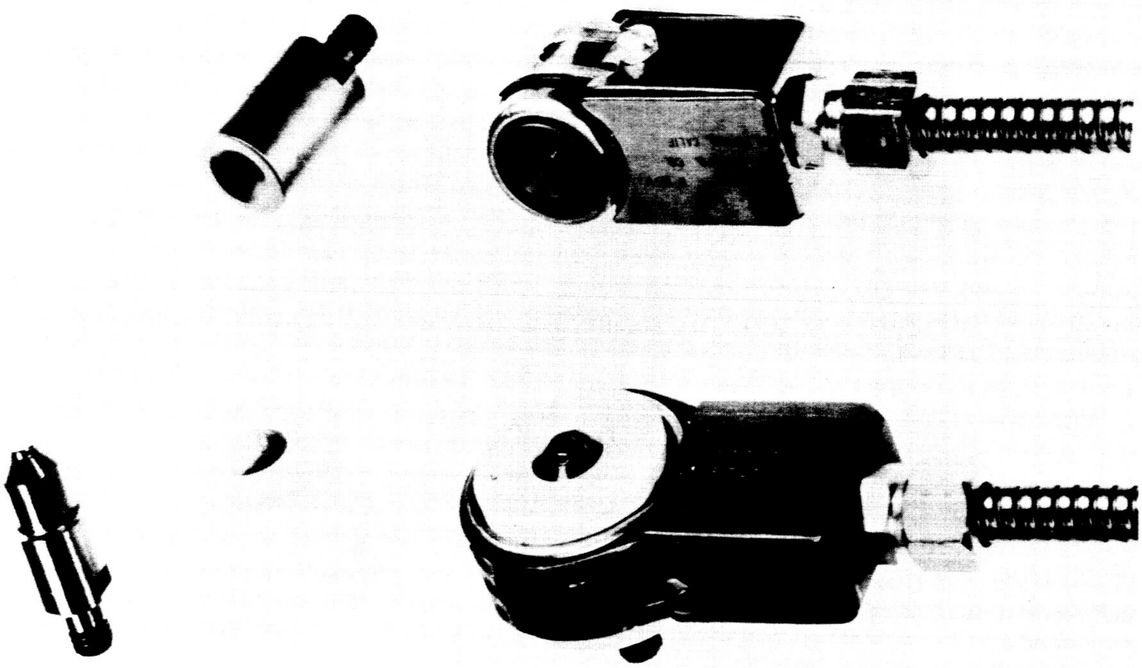


FIGURE 111. RESISTANCE-HEATED DIMPLING TOOLING

Courtesy of Zephyr Manufacturing Company, Inglewood, California.

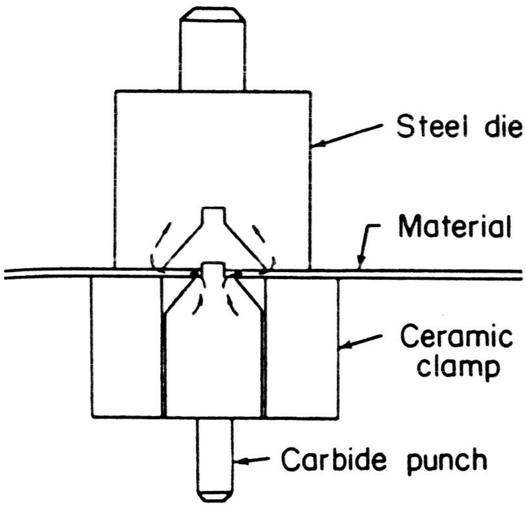


FIGURE 112. CURRENT FLOW FROM PUNCH TO DIE USED TO HEAT SHEET MATERIAL TO THE DIMPLING TEMPERATURE BY RESISTANCE (REF. 69).

Ceramic clamp heated between 500 and 600 F by a strap resistance heater so that the ceramic does not act as a chill ring.

The tooling consists of a solid die and a two-piece punch assembly. The die is made of high-temperature-resistant steel. This punch cone is a composite of Kentanium and steel base. Sometimes punches also are made of tungsten carbide. The pad is a special high-alumina composition. Strap heaters were used to heat the punch pad and die, to reduce heat-sink effects, and to eliminate thermal shock on the pad. The direction of current flow from the punch to the die used to heat the sheet metal to the dimpling temperature is shown in Figure 112. The dies also may be heated by induction, and such systems have been produced by one or more suppliers of dimpling dies (see Figure 109).

Material Preparation for Dimpling.

Sheet Quality. Factors that permit maximum formability in dimpling are consistent yield strengths from sheet to sheet, minimum thickness and flatness variations between sheets, and high-quality surface finishes.

Drilling Sheet. The quality of the drilled pilot hole has an important influence on the success of dimpling. The holes must be smooth, round and cylindrical, and free of burrs. Hand drilling is not recommended. Burrs or wire edges remaining around the holes may be detached during dimpling and lodge on the punch or die.

Pilot-hole sizes should conform to specifications applicable to aluminum alloys. The pilot holes should be drilled with suitable stub drills to produce holes with straight edges. Such holes are satisfactory for dimpling.

Deburring Drilled Holes. Care must be taken in deburring holes for dimpling. Only the material turned up by the drill at the edges of the hole should be removed. Hand deburring with a countersink cutter has proven satisfactory (Ref. 68). Power-driven countersinks that chatter are not satisfactory since chatter marks are potential sources of radial cracks.

A power-driven deburring tool* has been used successfully in production (Ref. 68). The tool is mounted in the chuck of a 1000-rpm pneumatic-drill motor, and a microstop is adjusted to cut the burr flush with the sheet surface. Such a machine produces a satisfactory deburr and leaves a smooth hole edge.

*Tool Number ZP339, The Zephyr Manufacturing Company, Inglewood, California.

Lubricants. Dimpling at both room and elevated temperatures is done dry.

Dimpling Limits.

Theoretical. The general theoretical predicability equation (Ref. 33) for dimpling based on the parameters indicated in Figure 105 is: .

$$\frac{H}{R} = \frac{(0.444)\,(\epsilon_{2.0})^{0.253}}{1 - \cos\alpha} \quad . \tag{31}$$

The value $\epsilon_{2.0}$ in the equation is the elongation in a 2-inch gage length for the material at the temperature of interest. Table XXXV gives elongation values for a number of nickel- and cobalt-base alloys. This list was compiled by Wood, et al. (Ref. 25). Figure 113 shows the relationship between ductility and temperature for the solution-treated René 41 nickel-base alloy and the L-605 cobalt-base alloy (Ref. 26). The L-605 alloy is somewhat more ductile than René 41. These curves suggest that both alloys might be dimpled at room temperature for best results.

Data reported by Republic Aviation Corporation (Ref. 29) indicate that Inconel X-750 can be satisfactorily dimpled at room temperature for sheet thicknesses ranging from 0.032 to 0.080 inch. They placed 1/16-inch-thick neoprene rubber pads between the part blanks and the die surfaces to modify the die radii and prevent coining of unsatisfactory dimples. Later work indicated that these pads were not necessary to produce good dimples; their use then was discontinued. The nominal fastener thicknesses produced in this Republic Aviation study are summarized in Table XXXVI for Inconel X-750 sheet both in the annealed (solution treated) condition and also in the aged condition.

Wilcox (Ref. 40) reported unsuccessful attempts to dimple René 41 both in the annealed and in the aged conditions at tool temperatures ranging from that of the room to about 950 F. Sheet temperatures probably did not exceed about 700 F. This work covered both 0.025- and 0.063-inch-thick sheets and was done on a Chicago Pneumatic Model CP450EA hot-dimpling machine. Dimpling in the aged condition would be expected to be impractical because the elongation values are low. The failures in the annealed condition may have resulted from high H/R values in the tests.

TABLE XXXV. VALUES OF ELONGATION IN A 2-INCH GAGE LENGTH FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS (REF. 25)

Alloy	Condition	Elongation in 2 Inches, per cent
	Nickel-Base Alloys	
Astroloy	Annealed	22
Hastelloy	Solution treated	43
Carpenter 901	Aged at 1400 F	23
Inconel X-750	Annealed	50
Inconel X-750	Annealed and aged at 1300 F	24
Inconel 700	Solution treated and aged at 1600 F	28
Inconel 702	Solution treated and aged at 1400 F	36
M-252	Solution treated and aged at 1400 F	20-23
R-235	Annealed	43-48
R-235	Solution treated and aged at 1450 F	27
R-235	Solution treated and aged at 1600 F	27
RA-333		43
René 41	Solution treated	30-50
René 41	Solution treated and aged at 1650 F	12 (1 in.)
René 41	Solution treated and aged at 1400 F	9 (1 in.)
Udimet 500	Solution treated and double aged	18
Udimet 600	Hot rolled	20
Udimet 700	Solution treated and double aged	18
Waspaloy	Solution treated and double aged	28
D-979	Solution treated at 1850 F	40.5
D-979	Solution treated at 2050 F	68
D-979	Solution treated and double aged	13
	Cobalt-Base Alloys	
L-605	Solution treated	64
J-1570	Solution treated and aged at 1400 F	25
J-1570	Solution treated and aged at 1650 F	15
J-1650	Solution treated and aged at 1400 F	27
J-1650	Solution treated and aged at 1600 F	20
S-816	Solution treated and aged at 1400 F	35

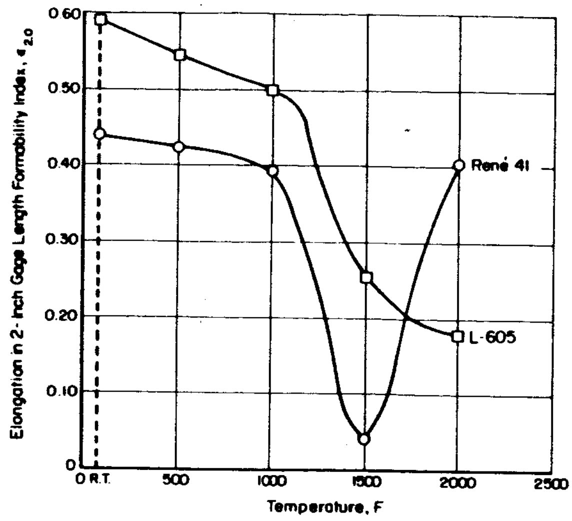


FIGURE 113. RELATIONSHIP BETWEEN ELONGATION AND TEMPERATURE AS DETERMINED IN TENSILE TESTS ON SOLUTION-TREATED SPECIMENS (REF. 26)

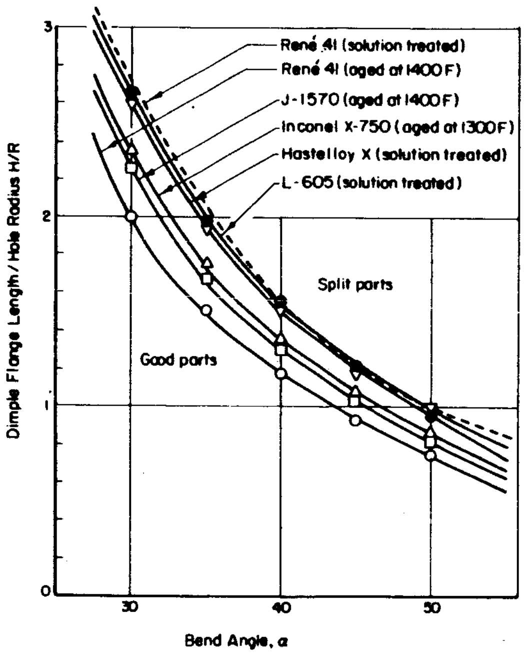


FIGURE 114. THEORETICAL RELATIONSHIP BETWEEN H/R RATIO AND BEND ANGLE FOR THE DIMPLING OF SELECTED NICKEL- AND COBALT-BASE ALLOYS (REFS. 25, 26)

TABLE XXXVI. NOMINAL FASTENER THICKNESS PRODUCED FOR INCONEL X-750 (REF. 29)

Minimum Material Thickness, inch	AN 426 Rivet Size[a]	AN 509 Screw Size[b]	HS 67 Rivet Size[c]
		Annealed Condition	
0.025	-4, -5		
0.032	-4, -5, -6		
0.043	-4, -5, -6	No. 8	-5
0.050	-4, -5, -6. -8	No. 10	-5, -6, -8
0.062	-5, -6, -8	No. 10, 1/4	-5, -6, -8, -10
0.072	-6, -8	No. 10, 1/4	-6, -8, -10
0.081	-6, -8	No. 10, 1/4	-6, -8, -10
		Aged at 1300 F for 20 Hours	
0.025	-4, -5		
0.032	-4, -5, -6		
0.040	-4, -5, -6	No. 8	-5
0.051	-4, -5, -6, -8	No. 10	-5, -6, -8
0.062	-6, -8	No. 10, 1/4	-6, -8, -10
0.072	-6, -8	No. 10, 1/4	-6, -8, -10
0.081	-6, -8	No. 10, 1/4	-6, -8, -10
		Dimpling Beyond Nominal Fastener Thicknesses (Both Annealed and Aged)	
0.020	-3, -4, -5, -6, -8	No. 8, No. 10	-5, -6, -8, -10
0.025	-6, -8	No. 8, No. 10, 1/4-28	-5, -6, -8, -10
0.032	-8	No. 8, No. 10, 1/4-28	-5, -6, -8, -10
0.040	-8	No. 10, 1/4-28	-6, -8, -10
0.043	-8	No. 10, 1/4-28	-6, -8, -10
0.050		1/4-28	-10

(a) AN 426 - 100-degree flush head rivet.
(b) AN 509 - 100-degree flush head screw.
(c) HS 67 - (close-tolerance head), hi-shear 100-degree flush head rivet.

Figure 114 and Table XXXVII show the calculated relationships at room temperature between the H/R ratio and the bend angle, α, as determined by Wood, et al. (Refs. 25,26,33), for three nickel- and two cobalt-base alloys. As expected, the alloys are easier to dimple as solution treated than when aged. These data predict that good parts will be formed for values of H/R under the curves while splitting will occur if the experimental H/R values fall above the curves. Similar charts can be prepared for other alloys using Equation (31) and appropriate elongation values such as those given in Table XXXV.

TABLE XXXVII. ROOM-TEMPERATURE DIMPLING LIMITS FOR SELECTED NICKEL- AND COBALT-BASE ALLOYS TO PREVENT RADIAL SPLITTING AT EDGE OF HOLE (REFS. 25, 33)

Alloy	Condition	Dimpling Limits, H/R for Various Bend Angles, α				
		30 deg	35 deg	40 deg	45 deg	50 deg
Hastelloy X	Solution treated	2.60	1.94	1.50	1.18	0.95
Inconel X-750	Aged (1300 F)	2.35	1.75	1.35	1.07	0.86
René 41	Aged (1400 F)	2.00	1.50	1.17	0.92	0.74
J-1570	Aged (1400 F)	2.26	1.67	1.30	1.03	0.82
L-605	Solution treated	2.66	1.98	1.53	1.20	0.98
René 41[a]	Solution treated	2.71	2.05	1.57	1.20	1.01

(a) Reference 26.

Conditions of heat-treatment and dimpling temperatures affect the limits given in Table XXXVII.

The usefulness of Table XXXVII can be illustrated in the following example (Ref. 25):

Problem: Determine the maximum length of dimple flange, H_{max}, for the L-605 alloy in the solution-treated condition using a hole radius of 1/4 inch and a bend angle of 42 degrees.

α = 42 degrees; R = 0.250 inch

By interpolation, H/R = 1.398 when α = 42 degrees
H_{max} = (H/R) (R) = 1.398 x 0.250 = 0.350 inch.

Dimpling Temperatures. There appears to be essentially three temperature ranges for fabricating the nickel- and cobalt-base alloys:

(1) In the vicinity of room temperature

(2) Below the precipitation-hardening temperature

(3) At about the solution-treating temperature.

Some of the nickel-base alloys, such as Inconel X-750 and the M-252 alloy, in thin sheet have been successfully dimpled at room temperature both in the annealed and also generally in the aged condition (Ref. 70). For dimpling sheet above about 0.020 inch thick, better results are obtained at 600 F. Figure 113 indicates that the solution-treated René 41 and the annealed L-605 alloy can best be dimpled at room temperature (Ref. 26). The condition of heat treatment is important. Wilcox (Ref. 40) was unable to dimple 0.025 or 0.063-inch-thick René 41 in the aged condition for either 5/32-inch Hi-Shear rivets or 1/4-inch U. P. screws at temperatures up to about 950 F with conventional dimpling equipment. However, work at Republic Aviation (Ref. 71) and Boeing (Ref. 72) indicates that aged René 41 can be dimpled successfully at higher dimpling temperatures in the range of 1800 to 2000 F. For this higher temperature dimpling, the patented Zephyr resistance-heating method, illustrated in Figure 111, was employed. However, to date the Hastelloys have not been dimpled successfully with this method.

In elevated-temperature dimpling applications, the temperature to which the sheet is locally heated by resistance prior to dimpling is a function of the dwell time, the time of contact between the dies and the sheet prior to dimpling. The dwell time required to insure the correct dimpling temperature can be determined from test strips or coupons of the same sheet to be dimpled. The sheet is painted around the pilot hole with temperature-indicating lacquers or paints having the desired melting temperature. The test piece is clamped between the heated die and punch and held until the temperature-indicating material melts, noting the time that elapsed between the clamping in the die and the melting. This time is the required dwell time. The proper dwell time is variable and depends on the ambient temperature, the size of fastener, and the type and thickness of material to be dimpled. Actual production dwell times must nearly always be determined experimentally or based on the operations experience with other sheet having similar hole diameter and thickness.

Post-Dimpling Treatments. Normally nickel- and cobalt-base sheet is dimpled in the condition in which it is to be utilized. Therefore, no post-dimpling heat treatment is required. Also, if properly performed, the sheet will not warp or deform during dimpling and straightening or flattening of the sheet is not generally required.

Flash occurring at the edges of the dimple is common for all types of dimpling. It generally is removed after dimpling by drilling and deburring.

Properties of Dimpled Sheet. Properly dimpled holes may be expected to retain 85 to 95 per cent of the cross section and strength of the material around the rivet hole (Ref. 69). However, relatively few data on the strength of dimpled joints have been published. Table XXXVIII gives data obtained at Republic Aviation Corporation on the strength of dimpled joints of 0.020-inch-thick Inconel X-750 sheet (Ref. 29) made with stainless steel fasteners. The ultimate purpose of the brief study was to determine whether the use of 1/16-inch-thick rubber pads placed between the part blank and the die surface during room-temperature dimpling was beneficial to the strength of the dimpled sheet. The data in Table XXXVIII show higher strengths for joints where the padding was eliminated. All of the joints showed acceptably high strengths for either No. 10 screws or 1/4-inch rivets. Similar results were obtained on fatigue-life determinations for both types of fasteners, as is shown in Figures 115 and 116, for the No. 10 screws and the 1/4-inch rivets, respectively.

TABLE XXXVIII. STATIC STRENGTH OF INCONEL X-750 DIMPLED JOINTS (REF. 29)

Thickness, inch	Fastener[(a)]	Test Ultimate, pounds/fastener	Allowable Ultimate, pounds/fastener	Yield, pounds/fastener
0.020 (no rubber)	No. 10 screw	1338	1160	1090
0.020 (with rubber)	No. 10 screw	1300	1130	958
0.020 (no rubber)	1/4-inch rivet	1854	1610	1450
0.020 (with rubber)	1/4-inch rivet	1656	1440	1290

(a) Stainless steel fasteners were used.

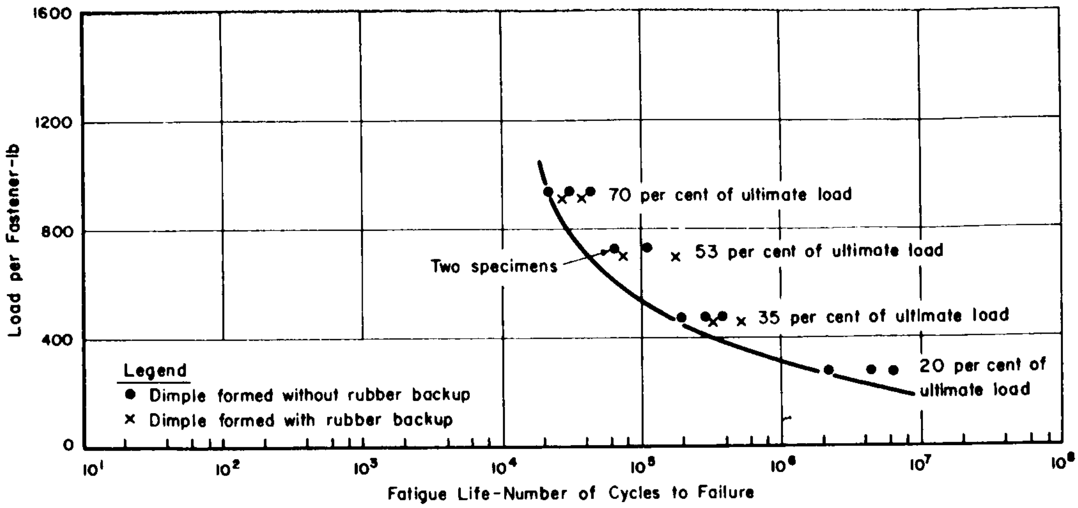


FIGURE 115. S-N FATIGUE CURVES FOR 0.020-INCH-THICK INCONEL X-750 SHEET FASTENED WITH NO. 10 STAINLESS STEEL SCREWS (REF. 29)

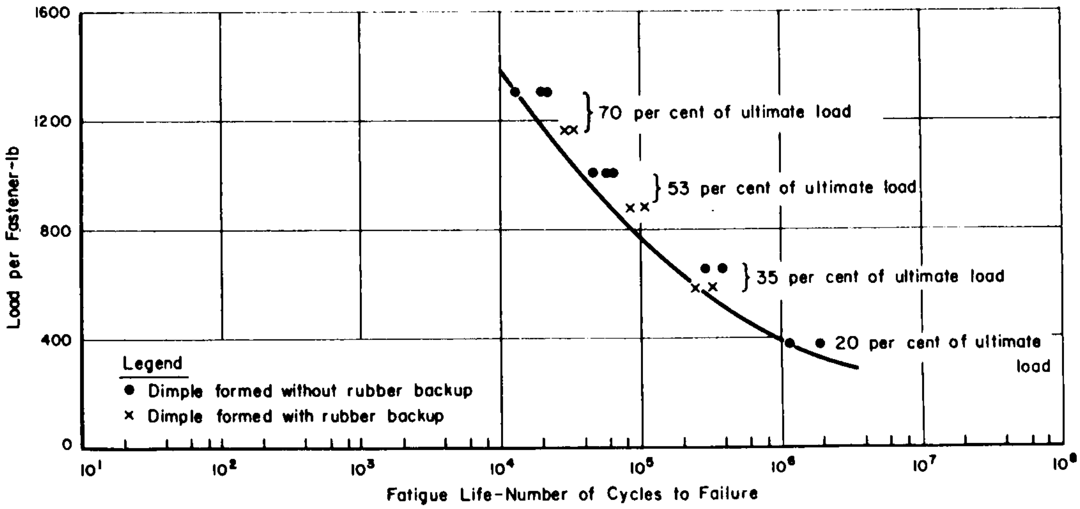


FIGURE 116. S-N FATIGUE CURVES FOR 0.020-INCH-THICK INCONEL X-750 SHEET FASTENED WITH 1/4-INCH STAINLESS STEEL RIVETS (REF. 29)

JOGGLING

Introduction. A joggle is an offset in a flat plane at the same angle. Joggling permits flush connections to be made between sheets, plates, or structural sections. The bend angle for joggles is usually less than 45 degrees, as indicated in Figure 117. Because the bends are close together, the same flange will contain shrunk and stretched regions in close proximity to each other. The two types of deformation tend to compensate for each other.

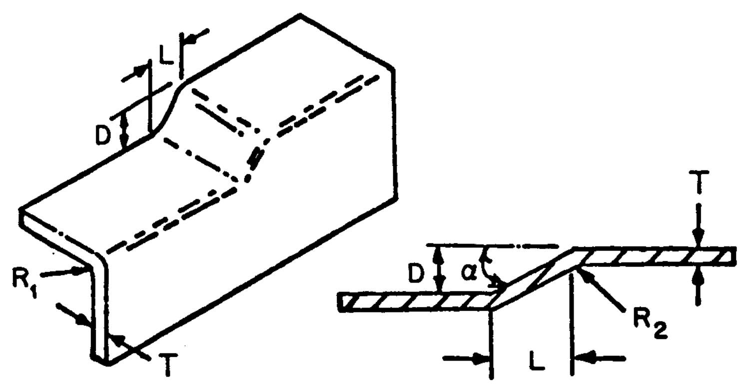


FIGURE 117. JOGGLE IN AN ANGLE (REF. 33)

α = Joggle bend angle
D = Joggle depth
L = Joggle length or runout
T = Thickness of workpiece
R_1 = Radius on joggling block
R_2 = Radius of bend on leading edge of joggle block.

Equipment. Joggles may be formed either in straight or curved sheet-metal sections by a variety of techniques. A separate operation may be used to obtain a joggle or the joggle may be formed as part of another forming operation. Presses with special joggle dies are often employed for forming joggles in angles and channels. Hydraulic presses are preferred for joggling at elevated temperatures because they simplify control of pressure and dwell time. The joggles usually are formed either by a wiping action or a section movement, as shown in Figure 118.

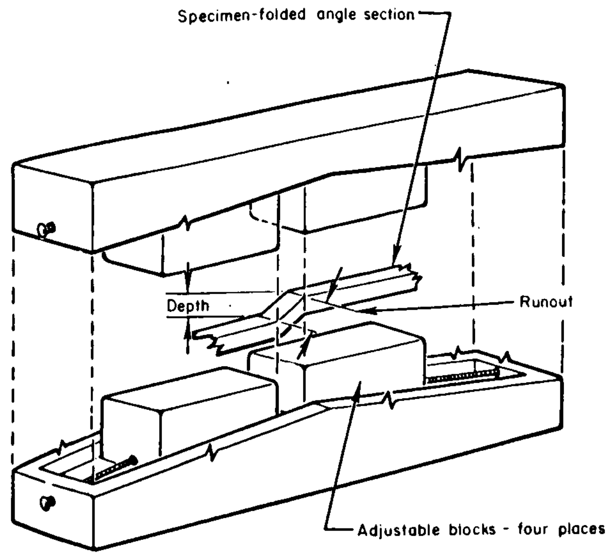


FIGURE 118. BASIC METHODS OF FORMING JOGGLES (REF. 33)

Tooling. Joggling of nickel and cobalt alloys often is done at room temperature. Nickel-chromium-molybdenum tool steels will give satisfactory service when heat treated to R_C 50-55. For higher temperatures, tooling constructed from high-strength, heat-resistant alloys or ceramic materials must be used.

A schematic drawing of a universal joggle die is shown in Figure 119.

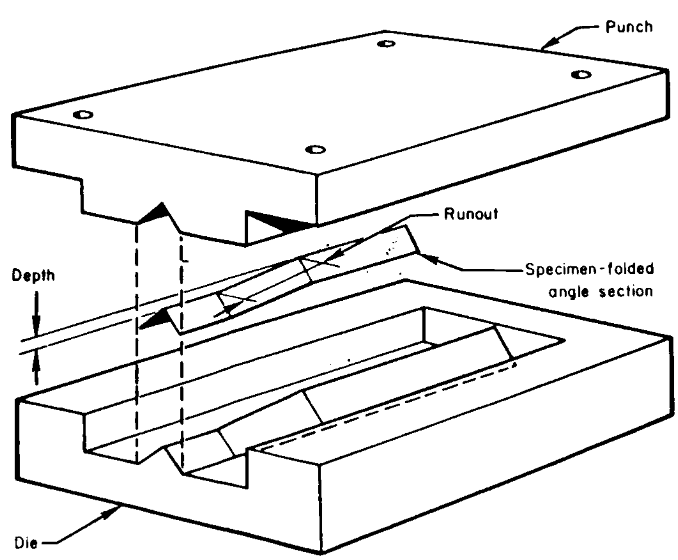


FIGURE 119. UNIVERSAL JOGGLE DIE
Courtesy of North American Aviation, Inc., Los Angeles, California.

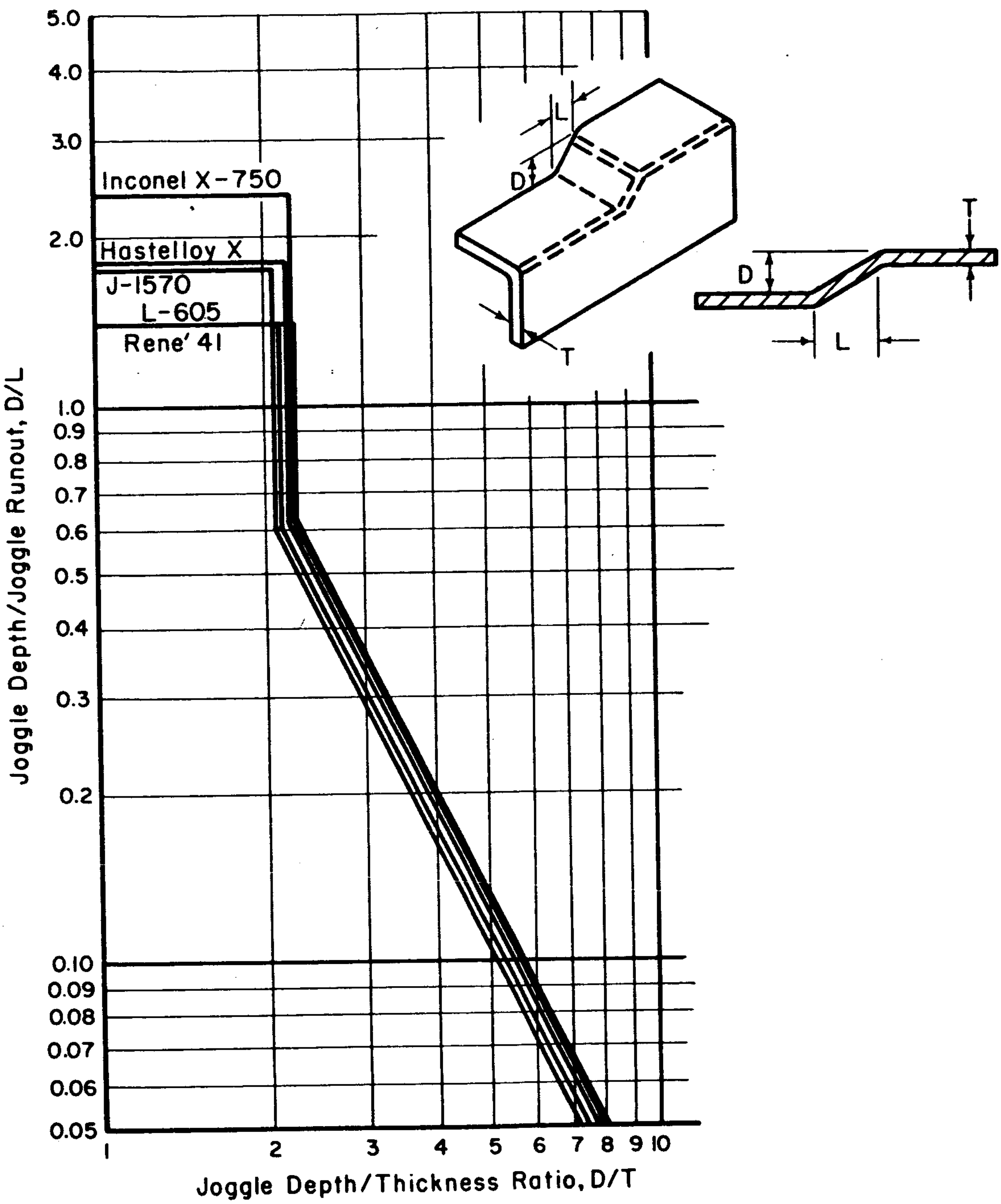


FIGURE 120. FORMING LIMITS FOR JOGGLING OF NICKEL AND COBALT ALLOYS IN THE SOLUTION-TREATED OR ANNEALED CONDITION (REF. 33)

This type of tooling requires an additional hydraulic cylinder to apply horizontal forces to clamp the side of the angle specimen to the die. Suitable shims are added to the die to produce the shape desired in the part. For production runs, mated rather than universal, adjustable joggle dies are usually used.

Material Preparation. Precautions covered in the section on blank preparation apply to the preparation of sheet for joggling.

Lubricants. Lubricants are generally used in the production joggling of nickel- and cobalt-alloy sheet metal. The high-pressure drawing lubricants containing inert filler and high film strength would be satisfactory. If a sulfurized oil or grease is used complete removal must be obtained before any thermal treatment is used on the parts.

Joggling Limits. Wood and associates (Ref. 33) included experiments on L-605 and René 41 in their study of the relationships between the properties of the workpiece and the formability limits in joggling. Formability limit charts, based on data for several nickel and cobalt alloys in the solution-treated condition, were constructed from a knowledge of the properties of the material and joggling geometry (Ref. 33). These are shown in Figure 120. Inconel X-750 is shown to have the best formability in joggling of the alloys shown. The joggle depth can be about 2.5 times the runout length for this alloy. The joggle-depth to material-thickness ratio is approximately the same for all of the alloys shown. The L-605 alloy appears to have slightly better formability than the others with respect to this ratio. The common types of buckling and splitting failures encountered in joggling are illustrated in Figure 121.

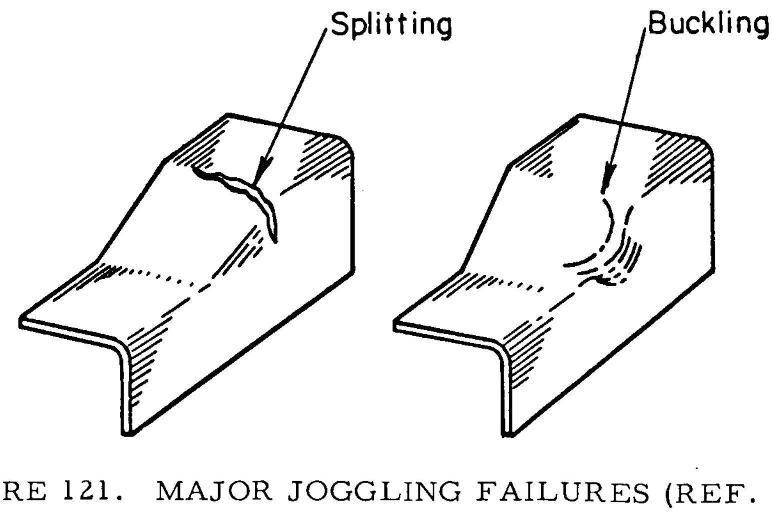


FIGURE 121. MAJOR JOGGLING FAILURES (REF. 25)

An empirical approach that may be used to choose joggle dimensions is described in a North American Aviation Specification (Ref. 73). The length or runout, L, of the joggle, shown in Figure 117, can be determined from the following formulas and the factors A, B, and C given in Table XXXIX.

(1) If the joggle depth is greater than A, the length of the joggle runout equals B times the joggle depth or $L = BD$ (when $D > A$).

(2) If the joggle depth is less than A, the length of the joggle runout is equal to the square root of the joggle depth times the quantity C minus the joggle depth or

$$L = \sqrt{D(C - D)} \qquad \text{(when } D < A\text{)}.$$

(3) For joggles in flat sheets, the projected distance between tangents may be determined from the equation for reverse curve as follows:

$$L = \sqrt{D(4R_2 + 2T - D)} \qquad \text{(see Figure 117)}.$$

Values suggested for minimum runout and minimum bend radii are given in Table XXXIX for several nickel-base alloys.

TABLE XXXIX. JOGGLE-FORMING-LIMIT FACTORS (REF. 73)

Material	Minimum Bend-Radii Factors: Bend Factors, R/T[a]	Minimum Joggle-Runout Factors: Joggle Factors[b] A/T	B	C/T
Inconel 600	1	1.2	2	6
Inconel X-750	1	1.2	2	6
Inconel 718 Condition A	1	1.2	2	6
René 41	2	2.0	2	10

(a) To obtain bend radius multiply R/T value in this table by material thickness, T.

(b) To obtain A and C, multiply A/T and C/T values in this table by material thickness, T.

Post-Joggling Treatments. Springback in joggles formed at room temperature or slightly elevated temperatures may be 5 to 10 per cent. The parts are generally overbent to compensate for the springback.

Joggled and formed parts generally are solution heat treated and aged after joggling. Clamping the parts in fixtures helps reduce distortion during the heat treatment. Any lubricant residue must be thoroughly and completely removed after joggling if the parts are to receive a thermal treatment.

SIZING

Introduction. Sizing is a final forming operation used to bring preformed parts within the desired tolerances. When form tooling has been properly designed to account for the predictable springback in the nickel and cobalt alloys, very little sizing should be required. Generally tolerances of plus or minus 0.030 inch can be obtained in forming these alloys. When fitup problems require closer tolerances a sizing operation is usually required.

Sizing of nickel or cobalt alloys might be accomplished by hand working or by hot sizing in desired fixtures. The former method is more commonly used. Alloys that age near the hot-sizing temperature can cause considerable difficulty and sometimes require more than one operation to obtain the desired results.

Benching. Benching is a hand-forming operation used to bring parts produced by plastic deformation to the desired tolerance. It consists of placing a free formed part over a male die of the desired dimensions and beating the part with lead strips. The term "benching" is used because the work is generally carried out with the die lying on a workbench.

Since most of the materials are work hardened by the previous forming operations they require a considerable amount of benching time; sometimes they crack during benching. Best results are obtained by annealing or solution treating the materials after forming and before benching. Parts made from many materials can then be heat treated after benching to obtain the desired properties. Benching after heat treatment should be avoided because residual stresses may be developed in the part that may be detrimental to its structural function (or "integrity").

Hot Sizing. Hot sizing utilizes the creep-forming principle to produce parts accurately formed to specified dimensions by the controlled application of pressure, temperature, and time. Two methods of hot sizing commonly employed in production are hot-press sizing and hot sizing in fixtures placed in conventional furnaces. In the first method, horizontal and vertical pressures, usually applied by presses, force irregularly shaped parts to assume the desired shape against a heated die. The pressure generally is applied in a vertical direction, the horizontal force resulting from reaction with rigid tooling. The pressure used should be the minimum required to form the part from the particular sheet thickness and alloy. Forces that approach the yield strength of the material at the forming temperature are used.

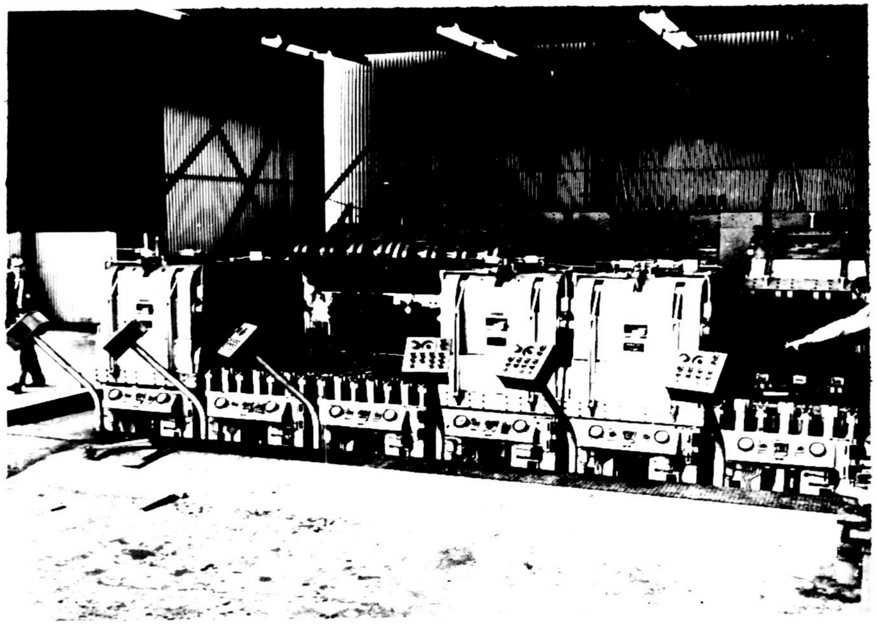
In the second process, parts are wedged in fixtures to obtain the necessary pressures, and then the assembly is heated in a conventional furnace. This method is simpler and cheaper because expensive hot-sizing presses are not required.

Temperatures from 950 to 1600 F are required to hot size nickel and cobalt alloys. The time required for sizing varies with the alloy, thickness of material, and temperature of tooling. Most production operations are regulated to take place between 10 and 30 minutes. After forming or sizing, parts are removed from the die and air cooled. The parts are expected to retain the room-temperature shape of the sizing die.

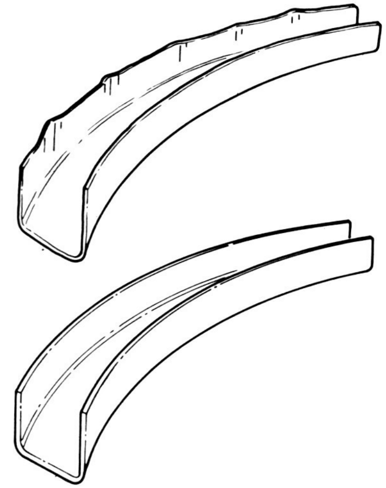
Hot sizing may be used for parts cold formed to rough dimensions by brake press, drop hammer, rubber, Hydropress, forming, or deep drawing processes. The temperature used for hot sizing is either at the solution-annealing or below the aging temperature for the alloy.

Equipment. A hot-sizing device consists of two heated platens, one mounted directly over the other. The upper platen is hinged so that it can be opened to expose the lower platen. The upper platen is operated by hydraulically actuated jack rams. The platens are heated either by gas firing or electrical-resistance heating.

Figure 122 shows an electrically heated hot-sizing press that has a bed 24 feet long by 4 feet wide (Ref. 74). This press is of the clam-shell design and consists of six units on a single frame. It can be operated either as a single press to make parts 24 feet long or as six smaller, individual presses. Each unit of the press has its own clam-shell top closure and four hydraulic clamps. Horizontal pressure is applied through hydraulic cylinders located in the rear of the press, not shown in Figure 122. The figure shows three of the individual units in the open position and three closed. The dies are heated by electrically heated platens as is shown schematically in the lower right corner of Figure 122. Vertical pressures up to 120 tons are available with each unit, and horizontal cylinders apply side loads



Hot-size press



Principle:
heat and pressure

Hydraulic cylinder pressure

Electrically heated platen

Part

Die

FIGURE 122. HOT-SIZING PRESS

Courtesy of North American Aviation, Inc.,
Los Angeles, California.

up to 75 tons. The presses for each unit are controlled individually. For smaller applications, single-, double-, or triple-unit presses may be installed as the expected operation dictates. This type of unit generally is used for hot sizing at temperatures below the aging temperature for the alloy.

No special equipment is necessary for hot sizing with wedge-type fixtures. Tooling can be made that will lock a part into position when wedges are driven between retaining rings and dies. Then the entire assembly is placed in a furnace. Figure 123 shows the principle of design of a number of hot-sizing fixtures. One of these fixtures contains electrically heated platens and can be used in a conventional arbor press as shown in Figure 123 (lower right corner).

Except for the wedge-type hot-sizing tool for use on an arbor press (see Figure 123), the pressure attainable in wedge sizing is limited and generally can be applied in only one direction. Wedge-type tooling is often used for sizing parts during solution-annealing treatments.

Tooling. In the selection of tooling materials for hot sizing, the effect of cycling the tools from room temperature up to 1500 F must be considered. Most tool steels will lose their strength at this level, and the application may justify the consideration of superalloys. Tooling materials that soften or distort in service are of little value in sizing operations.

Hot-rolled steel can be used for small production lots, up to about 20 pieces, provided the sizing temperature does not exceed 1000 F. Scaling is a severe problem with these tools (Ref. 75).

High-silicon cast-iron (Meehanite) dies can be used for lot sizes up to 100 pieces at temperatures to 1100 F. Scaling restricts the use of this material at higher temperatures. Wire brushing after 35 to 50 parts and light sand blasting of the die surface after 100 parts removes scale.

Greater quantities of parts can be obtained from tooling made of quality-controlled nodular cast iron (high-silicon, nickel, molybdenum nodular cast iron). This material has been used at temperatures up to 1700 F.

Some other die materials which have shown promise for hot sizing are summarized in Table XL with their probable limitations.

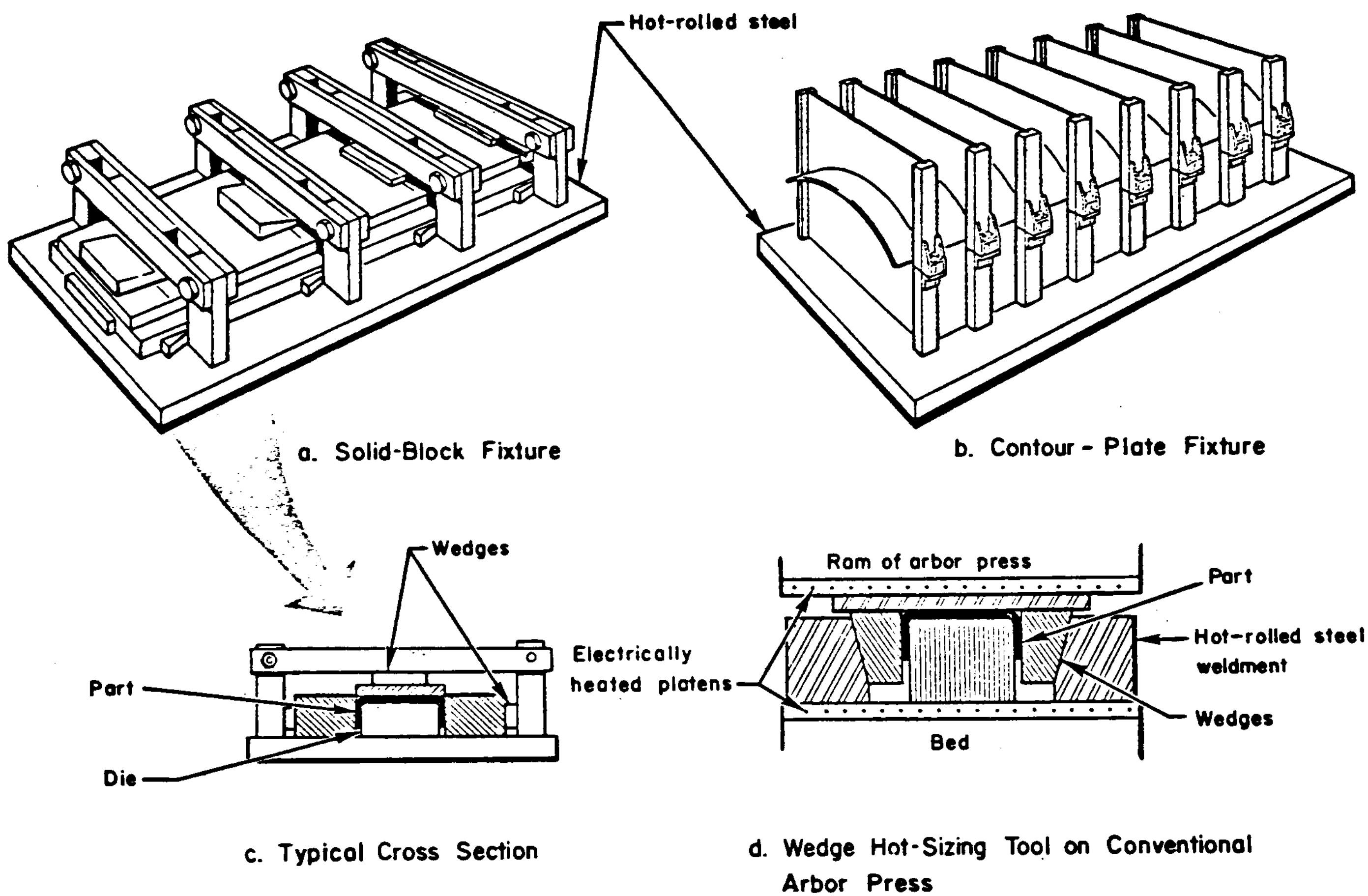


FIGURE 123. HOT-SIZING FIXTURES

Courtesy of North American Aviation, Inc.
Los Angeles, California.

TABLE XL. SUMMARY OF TOOLING MATERIALS FOR HOT SIZING (REFS. 75, 76)

Material	Number of Parts	Temperature Limit, F	Remarks
Hot-rolled steel	<20	1000	Not recommended for production tooling because of scale problems
Meehanite[(a)]	<100	1200	Wire brush at intervals of 35 to 50 parts; light sand blast after 100 parts; good resistance to oxidation
Nodular cast iron[(b)]	>100	1700	
Stabilized H13	200	1000	
Type 310 stainless steel	200	1500	
Type RA330 stainless steel	>200	1450	
Inconel	>200	1450	
Hastelloy	>200	1450	
Ceramic[(c)]		>1500	Ceramic dies are covered with stainless steel sheets, 0.050 inch thick
Modified H13[(d)]	>100	1300	Prehardened to RC 32-.36

(a) Meehanite is quality-controlled high-silicon cast iron.
(b) High-silicon, nickel, molybdenum nodular iron.
(c) Produced by Glasrock Products, Torrance, California.
(d) A chromium, molybdenum, vanadium tool steel produced by Columbia Tool Steel Company, Chicago Heights, Illinois.

The use of ceramic materials for dies is a rather new development. Castable ceramics allow the holes for heater wires to be cast in the die. The ceramic faces of the die are covered with stainless steel sheets about 0.050 inch thick. Face temperatures higher than 1500 F can be used with these tools.

Techniques for Hot Sizing.

Material Preparation. It is sometimes necessary to apply a protective coating or lubricant to the surface of the part to aid in forming and reduce oxidation, especially if the hot-sizing temperature is higher than 1000 F. Both the scale-preventive compounds and lubricants must be of the nonsulfurized type to prevent contamination.

Sizing Conditions. Because the hot-sizing process is used mainly to correct for springback and warpage in preformed parts, no definite forming limits can be given. The removal of springback and warpage in nickel- and cobalt-alloy parts depends on time, temperature, and pressure. In general, the higher the temperature, the shorter the necessary dwell time. The sizing temperature and the time at that temperature are more important than the pressure in hot sizing parts. Generally, little more than the weight of the dies is necessary to form the part to the final dimensions. The pressure should always be kept as low as possible to prevent deformation to the dies at the sizing temperature.

The temperature used for hot sizing nickel and cobalt alloys must be controlled within specific limits for the alloys. The alloys are generally sized just below the temperature range where the ductility starts to decrease from room-temperature values. Typical temperature ranges where some of the materials show a decrease in ductility are given in Table XLI. Working the materials within this range may result in cracking during the hot-sizing operation.

TABLE XLI. TEMPERATURE RANGE OF REDUCED DUCTILITY BELOW ROOM-TEMPERATURE VALUES FOR VARIOUS NICKEL AND COBALT ALLOYS (REF. 28)

Material	Temperature Range, F
Nickel-Rich Alloys	
Inconel 600	1100 - 1300
Inconel X-750	1100 - 1400
Inconel 700	1000 - over 1600
Hastelloy R-235	1200 - 1750
Waspaloy	900 - 1400
Rene 41	1300 - 1700
S-590	500 - 1200
Nimonic 80A	900 - 1650
Nimonic 90	900 - 1600
Cobalt-Rich Alloys	
S-816	1500 - 1750
HS-25 or L-605	1300 - 1600
V-36	1300 - 1600
HS-21	No significant change
HS-31	No significant change

Coffer (Ref. 77) found that hot sizing of René 41 was very difficult because it starts to age at 1100 F. The material decreases in ductility when the precipitation reaction starts. Increasing the temperature increases the precipitation reaction and has very little effect on the yield strength of the material. René 41 has very high creep resistance at temperatures below 1100 F. Consequently a number of sizing steps may be required to obtain close tolerances below this temperature.

Inconel X-750 parts have been hot sized successfully by heating at 1200 F for 4 hours (Ref. 78). The material was sandwiched in a steel-straightening fixture during the sizing treatment.

Between operations, hot-sizing presses are kept at a temperature of 1000 F to reduce the possibility of distortion of the platens during heating and cooling. When dies are changed, they are preheated to the forming temperature before being placed on the hot platens to minimize thermal shock. Dies and platens are insulated along the sides to prevent excessive heat loss. The dies are maintained at the desired temperature by heat transfer from the platens and controlled by thermocouples in the platens.

CONCLUSIONS AND RECOMMENDATIONS

Various types of research are expected to advance the art of deformation processing of nickel- and cobalt-base alloys. Developments in any of the areas mentioned below will probably increase productivity and decrease the costs of components fabricated from nickel- or cobalt-base alloys.

The development of primary deformation processes for nickel- and cobalt-base alloys are well advanced. Additional work in the theoretical aspects of metal movement during working as well as studies in friction and lubrication should be continued. No specific areas in primary deformation research directly related to nickel- and cobalt-base alloys were found.

Three types of research should be carried out in the secondary forming operations.

(1) Collection of information on the mechanical properties of nickel- and cobalt-base alloys that control the performance of sheet and plate in specific forming operations. The parameters that will permit predictions of formability at various temperatures are not ordinarily measured in routine tension and compression tests. With sufficient knowledge of the values of these

parameters and their normal range for commercial products, it should be possible to make better predictions of formability limits. This would considerably reduce the time involved in trail-and-error formability testing and permit the designers to extend the use of nickel- and cobalt-base alloys to more complex structures.

(2) One area of difficulty for secondary fabricators has been the sheet-to-sheet and lot-to-lot variation in formability of alloys purchased to the same specification. In many cases, it is desirable for the fabricator to perform certain additional costly operations to insure that the sheet can be properly fabricated. It would appear desirable that an independent study be initiated to determine the effects of slight variations in alloying elements and processing conditions on the formability of sheet. On the basis of such an investigation, it might be possible to prepare new specifications that would insure the delivery of sheet to secondary fabricators that would eliminate the need for additional processing prior to fabricating.

(3) Development work should also be directed toward improving equipment and tooling for forming nickel- and cobalt-base alloys by conventional and high-velocity processes. Elevated-temperature forming of cobalt-base alloys should be investigated further. Nickel-base alloys show such a small improvement with increasing temperature that additional work in this area is not warranted. The development of high-pressure rubber forming, either static or impact type, at room temperature for nickel- and cobalt-base alloys should be increased. There would be some benefit in the forming of these materials at higher velocities than those obtainable with conventional equipment. Development of tooling and limits of this type of forming should be undertaken. As with other materials, major improvements in forming some shapes from sheet and tubing can be expected from applying a counterpressure to minimize tensile stresses developed at the surface during forming. Drawing, flanging, and bulging operations are examples of processes that should give increased formability with a counterpressure.

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DEFORMATION PROCESSING OF NICKEL-BASE AND COBALT-BASE ALLOYS

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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